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Exploring Industry 4.0 Technologies Applications in the Healthcare Supply Chain

A literature review of digital technologies and their viable applications

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Abbreviations

AI - Artificial Intelligence

AGV – Automated Guided Vehicle

AM – Additive Manufacturing

AR - Augmented Reality

BDA – Big Data Analytics

DL – Deep Learning

EHR – Electronic Health Record

GenAI – Generative AI

IoT – Internet of Things

I4.0 – Industry 4.0

JIT – Just-In-Time

KET – Key Enabling Technology

HSC - Healthcare Supply Chain

ML - Machine Learning

NN – Neural Networks

R&D – Research and Development

RFID – Radio Frequency Identification

RPA – Robotic Process Automation

SC – Supply Chain

SCM - Supply Chain Management

UN - United Nations

VR - Virtual Reality

WIP – Work In Progress

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Abstract

The thesis explores the Healthcare Supply Chain (HSC) and the transformational potential of Industry 4.0 technologies which are destined to improve its efficiency, resilience, and performances at large. The thesis work explores the characteristics of such technologies, like Artificial Intelligence, Blockchain, Internet of Things (IoT), and Cloud Computing in the HSC, based on the existing literature and real-world examples. Interviews with experts in the industry also offer useful perspectives on their viability and current state of adoption.

Besides the recognition of some best practice examples about digital transformation, the thesis also examines the obstacles in the process, better known as "barriers to implementation". Ultimately, directions for further research are highlighted in the conclusions to stimulate and guide future investigations for this industry specifically.

Introduction

Context

The breakout of SARS-CoV-2 pandemic in 2019 has revealed the importance for the healthcare system to be enhanced, creating opportunity for development and innovation across the multiple areas and actors within the industry. Despite experts warning the world about a possible threatening pandemic, healthcare systems didn't evolve at the same pace of healthcare related discoveries, increasing the gap between cutting-edge tools and traditional healthcare mechanisms. The disparity resulted in the disruption of the industry, highlighting the fundamental need for mindset change and integration of both digital technologies and recent advancements [1].
Moreover, the sudden demand growth for SARS-CoV-2 prevention and treatment goods, such as vaccines, surgical masks, oxygen, alcohol and tests, emphasized the urgency for a flexible infrastructure within the healthcare supply chain, able to timely provide the necessary resources to healthcare providers and patients [2] *(Chatterjee et al., 2023)*. Disruptions could be partially avoided and prevented through the introduction of modern technologies and data sharing platforms, allowing for a synergetic action from key players in the sector. Engaging into healthcare digital transformation is not only a matter for facing future major catastrophes and pandemics, but for delivering a better and targeted service to patients, reducing costs and creating a fair working environment *(Leite et al., 2020)*.

Global healthcare spending was estimated at more than 11 trillion dollars in 2022 and projected to reach 18 trillion dollars in 2030 [3]. Hence, this sector is among the biggest and provide significant potential for digital transformation to be applied. However, investments are often lacking and fall behind other industries, contributing to the disparity in technological adoption. The introduction of the so-called Industry 4.0 technologies is still at a starting point in the sector, especially in the logistics, not yet unleashing all their potential benefits and creating room for market growth *(Ahsan & Siddique, 2022)*.

The thesis has the purpose of providing a basic knowledge of the Healthcare Supply Chain (HSC) and existing technology categories, included their main applications within the industry and some successful cases of implementation considering the different points of view for manufacturers, logistic carriers, and healthcare providers.

Research Questions and Strategy

The objective of the research is to comprehensively analyse the digital technologies available and their future within the healthcare supply chain. The topics are assessed on a higher level with few technical details for a wider understanding and provides the basics for further and deeper research on the impact of specific technologies and applications in healthcare and other industries. However, healthcare is considered to be lagging behind other industries, thus providing even more room for improvement.

To tackle the mentioned topic, the research questions the thesis addresses are the following.

- **Research question 1**: Which Industry 4.0 technologies are creating a bigger impact in the enhancement of the healthcare supply chain?
- **Research question 2**: Which benefits do Industry 4.0 digital technologies bring to healthcare supply chain?
- **Research question 3**: What are the main barriers slowing the adoption of digital technologies in the healthcare supply chain?

Thesis Structure

The thesis is structured into three chapters. The first one illustrates the founding concepts for the understanding of the real-world examples considered in the following chapter, thus providing an explanation of the basic structure of the HSC and the Industry 4.0 technologies. The second chapter delves into the realm of digital technologies currently explored for HSC purposes, while comparing their use in other industries. Lastly, the third chapter depicts the conclusions and tries to answer to the research questions. It highlights the different relevance some of the technologies are currently having and are thought to have in the sector, thus providing more insights especially on the use of Artificial Intelligence, Internet of Things, Big Data Analytics and Cloud Computing. The research highlights how different technologies are expected not to have the same impact on the HSC, with Artificial Intelligence, Cloud Computing, and Internet of Things as the most promising for their cumulative benefits when implemented, and Additive Manufacturing having limited impact on manufacturing of significant volumes, rather enhancing personalized care. Overall. the thesis underscores the relevance of developing tailored approaches for digital transition, to better match the individual entities' needs.

Chapter 1. Literature Review

Literature review is an essential component to develop research, as it is a founding collection and examination of the knowledge on the topic of the study and is subsequently used as baseline to build further contents on the matter. Its primary goal is to compare existing works to assess the state-of-the-art on the subject to find controversies, gaps and promote future research by steering research in specific directions *(Paré & Kitsiou, 2017*). In the context of HSC, this literature review aims to identify at a high level the key flows and actors, as well as the technologies that are and may become influent in the field, transforming the traditional HSC system into a digitalized and optimized one.

1.1. Purpose

The literature review has the aim to provide context on what the HSC is, as well on existing technologies that might be introduced to enhance its processes. Although HSC is a crucial component for the well-being of the final patients, and at large, of the worldwide population, some of these technologies are yet unexplored, underdeveloped and subject to multiple barriers to implementation, precluding the HSC from engaging in a rapid pace of innovation. Literature review allows to analyse existing knowledge on the topic and find possible further developments by identifying gaps and paradoxes. Future research stems from it, either drawing from generic studies (i.e. deductive) or building from specific cases (i.e. inductive) or combining both to transpose knowledge among diverse industries and areas.

1.2 Research strategy

1.2.1 References eligibility criteria

The research insisted on papers and articles concerning the basic definition of Supply Chain and further dived in Healthcare, illustrating the main logistic systems adopted specifically in the industry. Thereafter, an overview of Industry 4.0 and its technologies was provided.

Considering I4.0 includes multiple and complex technologies, a wide range of resources is available. However, relatively little knowledge has been built on healthcare and its unique features.

Resources were selected taking into account the following criteria.

Inclusion criteria:

- Articles about Supply Chain and Supply Chain Management
- Articles related to Healthcare Supply Chain
- Articles related to I4.0 and its technologies
- Articles concerning Supply Chain, Healthcare Supply Chain and I4.0 with its technologies

Exclusion criteria:

- Articles purely related to Healthcare treatments (not including Supply Chain)
- Articles targeting specific cases of Supply Chain in other industries
- Articles addressing the topics under a purely modelist approach.

The research prioritized recent resources in order to consider more up-to-date information. Though, some older ones were still used if represented the most comprehensive option or considered to be more reliable.

1.2.2 Research Methods

The resources used to conduct the research were obtained through multiple literature web engines, especially ScienceDirect, ResearchGate, Google Scholar and IEEE. In addition, several thematic websites were used. Some initial keywords were adopted, then paired with supplementary ones to find more accurate results.

Primary Keywords:

- Healthcare Supply Chain, Healthcare Supply Chain Management
- Digital technologies
- Industry 4.0
- Internet of Things, Additive Manufacturing, Cloud computing, Big Data Analytics, Additive Manufacturing, Advanced Automation, Blockchain, Artificial Intelligence

Secondary Keywords:

- Barriers, Challenges, Issues, Sustainability, Adoption, AI, IoT, Big Data, Key Enabling Technologies, Roadmap, Definition, Logistics, Distribution, Inventory Management, Warehouse, Applications.

1.3 Definition of Supply Chain and Supply Chain Management

The term "Supply Chain" (SC) encompasses several interpretations of multiple researchers and councils in the past decades. Among all, *Mentzer et al. (2001)* provided one of the latest and widely recognized definitions, proposing Supply Chain as a group of multiple parties that join their efforts to manage physical, information and financial flows to and from customers with the final goal to provide them a service or a product.

Therefore, Supply Chain Management (SCM) can be considered as the handling of a network whose independent parties and entities are regulated by business relationships, with the ultimate aim to satisfy customers' needs. The comprehensive system's management takes place through continuous monitoring and controlling of information, financial and materials flows, which lead to make specific decisions to optimize and enhance its functioning. In particular, the Council of Supply Chain Management Professionals refers to Supply Chain Management as the set of measures taken all along the Supply Chain to administer the necessary activities, involving the creation and preservation of the relationships with other parties, such as suppliers and stakeholders at large *(Vitasek, 2013).*

SCM coordinates efforts, objectives and performances of the three main sub-functions of a SC.

- **Logistics** consists of handling, warehousing and transportation of materials. Considering a company, logistics can also be classified as: ***inbound*** for incoming flows (e.g. orders delivered by external suppliers), ***outbound*** for outgoing flows (e.g. final product delivered to customers) and ***intralogistics*** for internal flows (e.g. movements occurring within the company boundaries) [4]. Common ultimate objectives of logistics are costs and lead times reduction, which are generally achieved through optimization of volumes and resources, management of distribution and storage centres and revision of transportation modes. For instance, low volumes might be shipped faster than higher ones, thus resulting in shorter lead time, but higher costs and customers satisfaction; higher volumes, on the other hand, allow to lower costs of production and transportation, but might cause both customers unsatisfaction if it results in longer lead time and satisfaction for lower final price [5].
- **Operations** group the activities contributing to value creation for a company on a daily basis. The nature of operations carried out depends on the company type. Operations may include a varied pool of activities which depend on the type of company. Manufacturing companies' operations are represented by production processes and quality control, logistic carriers and distributors' count on transportation activities, warehouse management, administrative tasks, etc (*Pauley M. K., 2019)*. Operations' main targets are the optimization of resources capacity and to ensure that core activities are completed smoothly by always looking to avoid disruptions and costs increase [6].
- **Procurement,** or **purchasing,** corresponds to "the activities associated with acquiring products or services [...]" *(Vitasek, 2013)*. Procurement should guarantee products and services needed by the company are obtained at the lowest feasible cost, thereby including the selection of the most suitable suppliers and the negotiation of such optimal costs and delivery modes.

Resource Management and **Information Workflow** are two further functions carried out alongside the previous ones. The former deals with "planning, organizing, and controlling of resources" with resources corresponding to workforce, equipment and materials. The latter checks whether information is flowing along the supply chain and assures a good communication level among parties to prevent and avoid flaws and disruptions *(Albrecht et al., 2023).*

1.4 Healthcare Supply Chain

1.4.1 Overview of Healthcare Supply Chain

Healthcare Supply Chain (HSC), refers to the healthcare specific distribution network and underlying mechanisms, starting with the production, followed by the distribution and concluding with the administration of drugs and medical goods (or, alternatively, the use of equipment for medical purposes). Considering the diverse goods taking part to the process, such as drugs, blood bags and medical devices, the HSC is quite complex to be enhanced *(Dixit, et al. 2019).*

Main actors in the HSC can be categorized as follows, each being the key player of a step within the chain *(Lenin, 2014; Betcheva et al., 2021)*:

- **Suppliers** provide manufacturers chemicals for drugs, various materials for packaging and equipment (e.g. paper, plastic, metal) and components for medical devices.
- **Manufacturers** are mainly represented by pharmaceutical, medical devices and equipment companies. Within such companies are often included their research laboratories that develop new drugs and tools for medical aims. They often carry out training courses and conferences about recent discoveries and innovations in the industry, with the purpose to attract both investors and providers to enter their business.
- **Distributors, wholesale** and **logistic carriers**, which represent the central stage of the HSC and focus on handling, transportation and distribution to healthcare providers. Some of these functions might be overlapping with manufacturers, especially when they dispose of a well-established network and do not need external parties to take charge of an intermediary role.
- **Healthcare providers**, which are the final step and involve all kinds of facilities providing direct contact with customers (i.e. patients). For instance, hospitals, clinics and private practices. They have to ensure timely procurement of necessary items and efficient storage within the facility to grant an optimal service.

Some activities in-between manufacturers and providers may be carried out by external entities, such as handling, storage and packaging. Moreover, the chain might also end with retailers, for example pharmacies (or distributors) directly providing products to customers [7].

1.4.2 Logistic systems in HSC

In the healthcare industry, logistics plays a pivotal role to ensure smooth and effective delivery of sanitary care and services. Two level of analysis can be adopted: macro-logistic and micro-logistic.

Macro-logistics includes in the analysis entities beyond the healthcare providers. By capturing the big picture, areas such as procurement, transportation, distribution, relationship with stakeholders and suppliers are being considered. Conversely, micro-logistics equals the so called "last-mile logistics", or "internal logistics", thereby encompassing management of supplies within the facility (i.e. from delivery to the healthcare provider to final use for patients) [8].

Macro-logistics

The Healthcare Supply Chain involves complex mechanisms and multiple entities taking part to the processes. Two logistic systems are mainly being adopted to provide necessary goods to ultimate patients in hospitals and many hybrid variations are available to choose among and fit to requirements of each provider.

Centralized system

This configuration can be further declined into two sub-types *(Shamsuzzoha et al., 2020):*

- The "Traditional System" (Figure 1) is a widespread organizational model, which relies on an internal warehouse for hospitals, directly dealing with supplier to manage the current and future state of goods. By adopting this scheme, each entity (i.e. hospital or analogue entity) provides to its own need of drugs and equipment and engage in a tight communication with manufacturers and distributors in order to satisfy its demand.
- The "Centralized Hub System" (Figure 1) relies on a common warehouse for multiple providers. This model is structured into two phases: the former, in which goods are delivered from multiple suppliers to the warehouse; the latter, in which hospitals having access to the warehouse can refill their internal stock. This configuration allows to

achieve savings, as the buying phase is aggregated. Therefore, it leads to overall lower costs of transportation and warehouse management for involved providers.

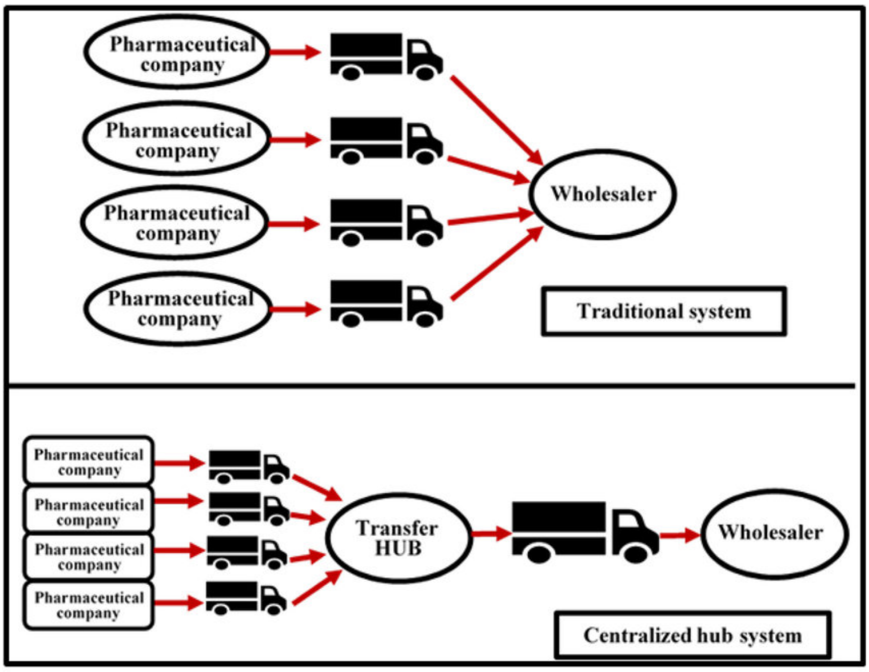

Figure 1. Schematic representation of the Traditional System and Centralized Hub System [9]

Transportation Pipeline System (TPS)

TPS is a configuration that lets hospitals rely on a third-party logistics (3PL) to aggregate all the necessary goods provided by multiple manufacturers into a single yet larger shipping option. The concept of outsourcing is fundamental for this model and despite leading to savings on an external warehouse, it also requires close communication and overall good relationships between entities to ensure an optimal performance and avoid disruptions.

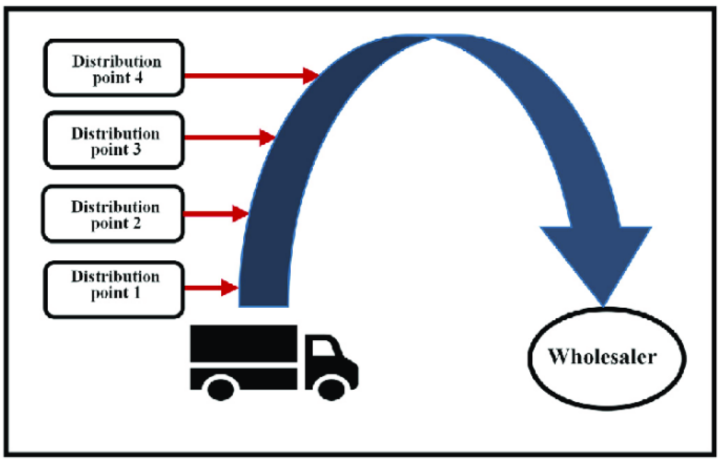

Figure 2. Schematic representation of Transportation Pipeline System [10]

On the one hand, the Central Hub System carry economic benefits over the Traditional System, as it allows hospitals to share warehouse management and transportation costs. On the other hand, TPS grants hospitals to focus on their core business (i.e. patients management and care) and to directly receive goods, avoiding a further shared warehouse.
However, the Central Hub System enable hospitals to have at disposal a greater amount of goods in the occurrence of major and sudden events that might significantly alter the demand for specific drugs and equipment. For instance, Covid-19 outbreak happening in single hospital can lead to increased demand of surgical masks compared to a steady demand in other healthcare centres, hence allowing the hospital to make use of a greater quantity already stored in the warehouse *(Shamsuzzoha et al., 2020).*

Micro-logistics

Within Micro-Logistics, Lean Manufacturing is considered to be a fundamental approach for continuous improvement of processes. Lean Manufacturing is a production and management methodology. The concept is rooted in 1950s, when engineer Taiichi Ohno developed the "Toyota Production System", a set of production methodologies to improve performances at the Japanese automotive company Toyota. Later becoming Lean Thinking, to not refer only to manufacturing, researchers have described it in many different ways, among which *"process or set of principles (Womack et al., 1990) […], approach (Taj and Morosan, 2011) […] and model (Alves et al., 2012)" (Bhamu & Sangwan, 2014).*
Therefore, Lean is proposed to contrast the so-called "muda", a Japanese term referring to "specifically any human activity which absorbs resources but creates no value" *(Womack & Jones, 1996)* and is based on the concept of "kaizen", meaning an amelioration in every aspect of life, as expressed by its ideator, the economist Masaaki Imai in 1986 [11].

Just in Time (JIT) is a management philosophy introduced in the context of Lean Manufacturing with the aim to minimize waste of resources (i.e. human and material). Funding concept for JIT is the "pull" logic, namely production is regulated by demand, preventing mismatch and consequently providing goods only when and where needed in the required amount *(Heizer et al., 2016).* The application of JIT within HSC needs an excellent synergy between healthcare providers and suppliers, but grants optimal stock levels within the hospital warehouse, as excessive amount of goods is avoided. JIT brings benefits and drawbacks: on the one hand, it maximizes the chances for drugs to be consumed before the expiring date while could become a dangerous approach in situations of considerable demand variability by increasing risk of stockout. Moreover, JIT is facilitated by the adoption of digital technologies allowing suppliers to access real-time data about demand, which can be in turn analysed to define possible patterns, reducing chances of shortages, warehouse stock and thus, fixed costs.

In order to achieve JIT (or set JIT as final and ideal objective), several tools and methods have been introduced and can be adopted, among which kanban is particularly suitable for healthcare.

Kanban is "an approach to visualize the workflow of a production system" *(Santos, Beltrão, de Souza et al., 2018).* Kanban is founded on some key principles [12]:

- **Visualize workflow** by using a board. Visualization is a key element to achieve transparency and for easier and immediate communication.
- **Limit work in progress (WIP)** to maintain some degree of flexibility for resources (i.e. slack) and avoid them engaging into an excessive number of tasks without reaching completion.
- **Measure and manage flow**, which is more predictable by applying the limit on WIP and results to be more sustainable for workers.
- **Make process policies explicit** allow clear rules to be easily respected. Some examples are quantity, timing and responsible figures for replenishment of items, WIP limit and conditions for an item to be shifted ("pulled") to the following state.
- **Feedback Loops** having a crucial role for improvements within the process and for evolutionary change.

By integrating kanban principles, hospitals can foster a more flexible and communicative organization with the advantage of improving stock levels and reduce excess and scarcity. It is particularly useful for management of healthcare providers' internal stock, as visualization of stock situation and overall functioning is clear and immediate to understand to medical staff.

Example of kanban adoption in hospitals is the so-called Two-Bin System: if needed, items are taken from the main bin, containing a fixed quantity of products; when the main bin is empty, it is moved to a dedicated slot in the warehouse, the refill bin becomes the main one and reorder of the products is triggered. This technique prevents staff from manually counting items left and send a new order request. However, some facilities do not have enough storage space to use the two-bin system for every product and errors can easily occur (e.g. mixing the bins; picking from refill bin; bin to refill is placed in the wrong spot and reorder is delayed).

Similarly, the "supermarket" kanban system is composed of rack divided in two sides (i.e. A and B): side A is dedicated to picking on a FEFO logic (First-Expire-First-Out); side B serves as stock [13], [14].

1.4.3 Flows within the HSC

Regardless of the industry (i.e. automotive, food and beverage, tech, etc.), supply chains consist of 3 main types of flows [15], which encompass most interactions and transactions between parties along the chain. Specifically, in the healthcare industry, it is possible to declinate them as follows *(Kitsiou et al., 2007)*:

1) **Physical Flow**, which takes into consideration all flows of tangible units, starting from manufacturers and ending to patients. Physical Flow can be further distinguished into:
   - ***Products Flow***: including the movement of all medical goods, for instance drugs, blood, vaccines, equipment, prothesis, flowing from manufacturers to healthcare providers and finally patients. Effective management of product flows is critical to maintain the availability and quality of healthcare products, minimize delays, and ensure that products are safe and effective for patient use.
   - ***People Flow***: involving the management of people, such as healthcare professionals (doctors, nurses, and administrative staff), patients and their families. Efficient people flow ensures timely care for patients, better workload management for professionals, and prompt communication with patients and families. Within hospital settings, people flow has a key role in coordinating patient admissions, transfers, and discharges, in order to assign resources where they are needed the most [16].

   Despite being mainly unidirectional, some flows in the HSC take place in the opposite direction; such situations are, for instance, returns of defective equipment, expired drugs, contaminated material and hazardous waste for special recycling systems.

2) **Information Flow**, which involves the transmission of any kind of data: orders, updates, tracking information and patient records are a few examples of information interchange among the different parties along the supply chain. Formerly taking place on paper, nowadays the information flow is supported by digital systems and especially

by the use of cloud-based tools. Modern technologies not only provide different entities access to the data they need at the proper moment, but also favour decision-making processes and coordination among parties while safeguarding patients' privacy *(Kneck et al., 2019).*

3) **Financial Flow**: this includes all financial transactions, which are a key aspect of the HSC, involving payments between entities such as healthcare providers, insurance companies, suppliers and patients. This flow includes processes such as management of insurance claims, reimbursement to healthcare providers, and patient billing. Efficient flows ensure that healthcare providers are compensated promptly, reducing financial strain and enabling them to focus on delivering quality care rather than on financial matters, thus contributing to transparency and accountability within the chain [17].

1.4.4 Issues and Challenges in the HSC

The HSC faces many complex challenges that affect its efficiency and reliability; while some issues are due to factors external to the system and yet less foreseeable, others are endogenous and can possibly be improved by making careful assessments and introducing tailored digital solutions.

Patients Management and Demand Variability

Differently from the other sectors and services, healthcare is further complicated because physical flows not only include products, but also customers (i.e. patients). Their management is intricate owing to multiple factors; for instance, demand for healthcare related services is highly unpredictable and easily influenced by sudden events (e.g. accidents, food poisoning) and major force ones (e.g. pandemics, natural disasters). These phenomena can consequently lead to prolonged waiting times, workforce misallocation, lacking availability of facilities, shortage of drugs and equipment. Thus, from such a high variability stems the intrinsic need of continuously adapting offer to demand and creating a synergetic environment for parties to work within *(Ageron et al.,2018).*

Lack of Coordination and Inventory Management

Coordination within global pharmaceutical supply chains is often limited, leading to inefficiencies and disruptions in the delivery of essential goods. Effective inventory management is crucial to prevent both stockouts and overstocks, which can be accentuated by the absence of accurate information about demand and result in higher costs. To better spread costs related to inventory management, healthcare providers might join forces and adopt a Centralized Hub System allowing multiple entities to share an external warehouse, thus not only lowering costs, but also creating room for goods sharing if necessary. However, this type of organization requires excellent communication between entities and might be difficult to adopt. Moreover, an efficient order management system is essential to ensure timely and accurate fulfilment *(Privett, Gonsalvez, 2014).*

Counterfeited Drugs, Contamination, and Regulatory Challenges

The proliferation of counterfeit drugs severely threatens the HSC, impacting all actors from pharmaceutical companies to patients. These products often contain incorrect or even toxic ingredients which can lead to harmful if not fatal outcomes for final users. Furthermore, this side market can impact pharmaceutical companies, damage their brand image reputation and consequently lead to sudden sales drops.

Contamination of pharmaceutical products further exacerbates the risk of compromising overall drug safety and efficacy. It leads to questioning the role of quality assurance and governmental institutions in charge of inspections and approvals (e.g. FDA, EMA), undermining population's trust in drugs and the healthcare system at large. At the same time, product recalls and legal liabilities that might arise additionally increase costs. Enhancing transparency through the implementation of blockchain is a concrete solution to transparency problems, but again international cooperation is essential to ensure the underlying mechanisms. *(Kritchanchai, 2014).*

Temperature Control and Expiration Check

Drugs, vaccines, blood bags and organs are delicate goods to distribute due to the stringent requirements on the transportation and stocking conditions. Optimal temperature, humidity and light must be ensured along all the steps in the chain as chemicals can more rapidly and easily react if these guidelines are not followed, provoking goods deterioration and precluding their safe utilization. In addition, products must be handled considering their expiration date, both to prevent waste and ensure quality treatments to patients *(Privett, Gonsalvez, 2014).* IoT technology greatly contribute to control and monitor such conditions through the use of sensors; gathered data can also be analysed for future use, while blockchain can again help tracking conditions without allowing their modification ex-post.

1.4.5 Barriers to adoption of digital technologies in HSC

According to UPS Supply Chain Expert Harvey Rickles at AHRMM Annual Conference (1999), HSC was quite behind in technological advancements and implementations compared to other industries' supply chains. Particularly, the gap could be quantified as about a 20-year lag. Such a discrepancy is still evident today due to many factors, or "barriers", that specifically affect the HSC more than other sectors *(Beaulieu and Bentahar, 2021)*. Barriers to implementation for I4.0 technologies can be distinguished based on the area they impact *(Cannas et al., 2023)*.

Financial barriers

Investments to integrate KETs within the HSC are demanding *(Raj et al., 2020)* and are concentrated at the first edge of the chain within pharmaceutical and medical devices companies (e.g. for R&D advancements and drugs discovery). At the starting end, incumbent manufacturers have enough funds to allocate significant investments in areas such as drugs and vaccines discovery, testing and production within their laboratories and plants; at the other side of the chain, the scenario is fragmented into a multitude of healthcare providers, mainly operating independently one from the other, which might be specialized in different medical treatments, geographically dispersed and thus presenting heterogeneous requirements.

Moreover, little evidence has been produced in the field to document the benefits and risks of adopting technologies within the HSC, thus preventing investors from funding projects *(Nimawat, Gidwani, 2021)*.

Organizational barriers

Resistance for implementation also comes from a lack of skilled workforce on the job market and, consequently, low turnover rate for supply chain related positions specifically trained to manage and improve the HSC. As a result, procedures are rarely enhanced and tend to be kept stable over time to ensure patients care is carried out.

Furthermore, within hospitals medical staff is often subject to high pressure and time constraints, precluding training opportunities on digital technologies and consequently hindering them to be properly adopted and integrated in the processes. Being patients' well-being the ultimate goal for healthcare providers, medical staff might withstand the use of new tools due to potential side effects on working procedures and patients, and time to be invested in the learning phase *(Chauhan et al., 2021)*.

Strategical barriers

Adoption is not only hindered by lacking training and skills, but also by a poor long-term commitment for change. Healthcare providers' management focus on performances related to their core competencies, rather than on improving the supply chain. However, better performances in procurement likewise reflect on an overall enhanced service for patients. Supply chain specialists are rarely involved to strengthen processes and resilience for hospitals, as funds are not sufficient, and allocation is concentrated on urgent matters and more significant areas. Therefore, few case studies have been developed, a roadmap for the proper introduction of technologies is still at an embryonic stage and little collaborations among academic entities and HSC actors are launched. Papers on the theme of digital technologies in the HSC generally address their use in healthcare (i.e. diagnostics and assistance) and pharmaceutical R&D, while applications on intermediary phases, such as inventory management, distribution, monitoring and forecasting are slightly explored; the theme is explored in SC at large rather than specifically focusing on the unique features of the HSC and deriving benefits. Lastly, actors are not prone to share successful strategies and achievements, thus slowing down the creation of a wider knowledge base for stakeholders and other parties to take part in the development *(Kumar et al., 2021)*.

Technological barriers

The most crucial factor contributing to technological resistance is patients' privacy. In many countries, paper still represents the preferred means for keeping track of patients' data, while little information is recorded on informatic systems. Existing tools are often outdated and not suitable for data sharing between parties and devices, while migration to newer systems has to be paired with proper training of users guiding them in a smooth transition. Some I4.0 technologies are at an early stage of development and their full potential is still to be discovered; as a result, their validity has not yet been proved by many applications in the HSC, contributing to the already existing gap with other sectors. Ultimately, obsolete medical devices are often unprovided with interconnectivity features, hindering the possibility to upgrade them and rather making it necessary to heavily invest in completely new tools *(Raj et al., 2020)*.

Legal barriers

I4.0 technologies have been introduced on the market relatively recently and official laws are lacking and incomplete, leaving some complex areas yet unregulated. This international vague scenario holds back many companies and healthcare providers from embarking on the digital transformation process due to its risks and potential future legal drawbacks. Legislation is missing not only regarding data treatment and ownership, but also for cybercrime and its boundaries *(Cugno et al, 2021)*. During the last few years, the European Union has started working on the first worldwide law about emerging technologies, the "EU AI Act", which was approved in the first quarter of 2024 and will become valid within the following 24 months. Other countries are working on legislation about data use and AI, but none of them is set to be comprehensive as the EU AI Act [18].

1.5 Industry 4.0

1.5.1 Basics of Industry 4.0

Industry 4.0 (or I4.0) is commonly used indicate the Fourth Industrial Revolution (4IR), the latest revolution considered to be taking place since early 2010s. Originally coined as *Industrie 4.0* in 2011, the term was used to refer to a national technological and strategic plan by the German government. Along the years it has become widely employed to encompass the adoption of emerging digital tools, especially in manufacturing, which exploits the increasing availability of data and the technological advancements to improve working conditions [19].

In the last decade, I4.0 has led to both technological and structural transitions, resulting in more efficient and possibly sustainable manufacturing processes. This evolution has not only impacted production lines, but also the workforce involved leading to the need for new skills to be acquired and new approaches to work to be implemented. Therefore, it has fostered a closer collaboration between humans and technology, steering customizable, flexible, and resilient practices.

Implementation of I4.0 relies on several founding principles:

- **Interoperability** refers to the capacity of machines to create connections with people and other devices through the Internet of Things (IoT) and Internet of Services (IoS) infrastructures. This level of connectivity grants a smoother flow of information and enables digital and non-digital systems to work together in a coordinated way (*Davis et al., 2020).*
- **Virtualization** pertains to the creation of a digital duplicate of the tangible world, especially machines, products and processes. The virtual model can be obtained by extracting data from the original through sensors and using CAD files to create a replica.
- **Decentralization** relates to the capability of Cyber-Physical Systems (CPS) integrated in intelligent factories (or "smart factories") to undertake the decision-making process in an autonomous way. This allows systems to be independent from human operators and flexible by requiring less centralized intervention.
- **Real-time capability** concerns the ability to gather, inspect and create instant insights from data for further exploration. This is crucial for optimizing and speeding decision-making and processes.
- **Service orientation** is about delivering services from CPS, human workers, or intelligent factories in general, via the IoS to enhance collaboration and efficiency *(Hermann et al., 2016).*
- **Modularity** pertains the ability of smart factories to deliver superior performances by modifying processes through the use of a flexible structure. This design allows them to be create more agile and flexible production systems which can be more easily and rapidly adapted to mirror changes (*Davis et al., 2020).*

1.5.2 Overview of the Industrial Revolutions

I4.0 stands on the shoulders of the preceding industrial revolutions by expanding the progresses they introduced. The First Industrial Revolution, which brought in the massive developments occurring in the latest decades of 1700, introduced water and steam powered mechanisation in factories, completely ran by human workforce beforehand. The Second Industrial Revolution, occurring in the early 20th century, brought about mass production with the help of electricity, leading to the assembly line system pioneered by companies such as Ford. The Third Industrial Revolution, which started in the late 20th century, ushered the era of automated production through electronics and information technology [20].

Building upon these innovative periods, Industry 4.0 harnesses the power of digital technology to create smart factories. It integrates systems and cutting-edge technologies resulting in autonomous systems that are capable of supervising and virtually replicate processes, and subsequently allowing to make decentralized decisions. Through a deep level of connectivity and smart automation, I4.0 enables real-time responses and a flexible and efficient adaptation to new requirements.

Moreover, I4.0 amplifies the impact of previous industrial revolutions by introducing a level of personalization never seen before. While the earlier revolutions were marked by the incremental enhancement of human labour with machines, leading to increased production volumes, and the automation of basic routine tasks, I4.0 is characterized by the fusion of physical, digital and biological worlds. This revolution not only advances again industrial production, but also redefines the direct role of humans in the business world, leading to a more innovative, sustainable, and customized production landscape *(Vaidya et al., 2018).*

1.5.3 Key Enabling Technologies

Four technology categories have been identified as the foundation of Industry 4.0 [21]:

- Connectivity, data and computational power include Internet of Things and its sensors, Cloud Computing and Blockchain, and refer to the technologies creating the basics for digital ecosystems.
- Analytics and intelligence, which reunite Big Data Analytics and Artificial Intelligence as well as its subsets, and stands for the methods and algorithms needed for transforming inputs (i.e. raw data) into meaningful insights [22].
- Human-machine interaction, which enables humans to benefit from technological assistance through the use of interface and devices; it includes innovations such as Virtual and Augmented Reality, Advanced Automation, Robotic Processing Automation (RPA) and Chatbots.
- Advanced engineering, which employs the most recent advancements in manufacturing and latest engineering developments to improve traditional processes and materials, for instance Additive Manufacturing, Renewable Energy and Nanoparticles.

Key Enabling Technologies (KETs) are the cornerstone of Industry 4.0. They include a diverse range of innovations that serve as the backbone for advanced industrial processes and products, creating value for companies and facilitating human tasks, especially repetitive ones. The most relevant technologies for the scope of this study will be introduced in the following section.

1.6 Digital technologies in Industry 4.0

1.6.1 Artificial Intelligence

Artificial Intelligence (AI) is a field of research in computer science with roots in the middle of the 20th century and represents the new frontier of technology. It aims to perform actions that would usually require a human component by combining Big Data and algorithms. It can emulate and simulate human behaviour, decision making process and ability to solve complex problems [23].

IBM describes Artificial Intelligence, or AI, as the new technological frontier that allows computers to emulate the peculiar human intellectual skills [24].

Machine Learning (ML) is a subcategory of AI that is able to use specific techniques allowing machines to learn from past experience and gradually become proficient at completing certain activities, as the human brain is able to do through "learning by doing". Big amount of data is fed into an algorithm, which is then employed to train, test and deploy a model. Once the model is satisfactory, it can be used to execute the needed and precise task [25].

Neural Networks (NN) are a subtype of ML and consisting of artificial neurons as a base unit. Neurons are organized in layers and are interconnected, creating a structure similar to the human brain reasoning scheme. They are organized into an input layer for incoming data, one or several middle layers for elaboration (i.e. "hidden" layer) and an output layer to create and transmit the final response *(Taherdoorst, 2023)*.

Deep Learning (DL) is then a subset of NN and is used to carry out more complex analyses. The more the layers, the more accurate the final result and intricate the problem-solving skills become. Deep Learning can thus be defined as Neural Networks with at least three intermediate layers as its functioning reproduce with higher precision the human brain [25].

Generative Artificial Intelligence (GenAI) is again a type of DL capable of creating media and texts from the start. By disposing of a growing number of assets to use as a generating pool of content, GenAI is consistently increasing its proficiency at interpreting human prompts (i.e. inputs) and deliver precise and realistic outputs [26].

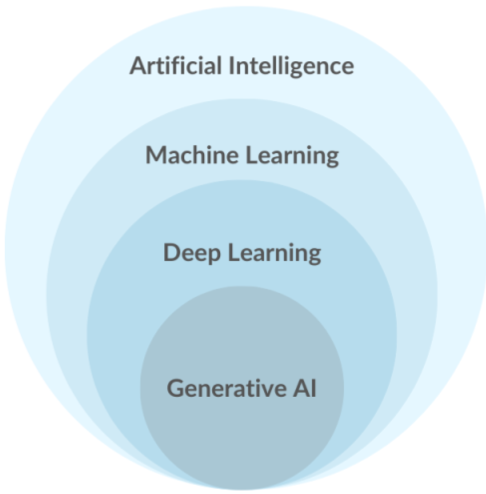

Figure 3. Representation of relationship between AI, ML, DL and GenAI [27]

Artificial Intelligence is probably the most flexible emerging technology among the listed ones. Its application in multiple areas and its benefits are tangible. First, AI is a precious ally in creating more accurate demand forecasting and in managing inventory; through the autonomous analysis of wide datasets, AI can assist in the optimal allocation of resources and in planning future activities by identifying trends, and thus lowering unpredictability caused by demand fluctuations [28]. In healthcare, this support is needed as demand is intrinsically highly variable and dependent on sudden events, hence it is crucial to minimize the unpredictable component by identifying all possible patterns. Its predictive capabilities can also help forecasting future failures and schedule preventive maintenance for equipment, as this could significantly increase waiting times for patients and cause postponement of moderately urgent surgery and diagnosis [29]. Moreover, it can aid in project restock modes to optimize inventory levels and avoid incurring in unnecessary costs: hospitals' warehouses are limited, and it is fundamental to effectively manage stock to avoid drugs to expire, higher fixed costs, shortages and overstock. AI can also be used to analyse cost trends and predict the optimal time for reorder to lower expenses: as prices continuously fluctuate, AI can suggest waiting for reorder of some items, thus avoiding extra costs and waste of delicate medical assets. Then, it can be used for interaction with customers as it can replicate human behaviour and language skills, as well answer basic requests, thus decreasing the pressure on operators and speeding up queries: for instance, it can be implemented within intelligent assistants to help healthcare providers track shipments and estimate arrival time. At last, AI can accelerate quality checks providing support in defect detection, thus avoiding unsafe drugs and equipment to be launched in the market, but also improve scheduling by examining the real time situation and suggest related best practices (e.g. in pharmaceutical companies, suggest when it is optimal to move production among machines considering predicted maintenance interventions and before causing disruptions; in hospitals, aid in the bed distribution system) *(Cannas et al., 2023).*

1.6.2 Augmented Reality and Virtual Reality

According to one of the many definitions, Augmented Reality (AR) can be recognized as a technology capable of taking information from the real-world as input and turning it into an immersive and interactive environment, by adding digital objects and features that are not present in its real version *(Al-Ansi et al., 2023)*.
Its invention roots back to 1968, when Harvard professor Ivan Sutherland created the first version of the modern headset. However, the term was first introduced in 1990 by Boeing researcher Tom Caudell [30].

AR usually introduces improvements involving sight and hearing, integrating digital content with the physical world using devices and software, such as specific screens and apps. This emerging technology is particularly appealing for companies creating metaverse ecosystems with the aim to exploit AR for commercial purposes *(Ozturkcan, 2020),* [31].
One of the main objectives of AR is to focus the user's attention on particular aspects of the external environment and allow for their better understanding. For instance, multiple companies are currently implementing AR solutions in their online stores to allow customers try on clothes and emulate objects (e.g. furniture, cars) in real-world settings, thus having a clearer perception of the shape, colour, size and fit on their figure and within the contiguous environment *(McCluskey, 2022)*.
The benefits of AR may also apply to the healthcare industry and as a learning tool, where it may have a significant impact by allowing users to get highly detailed 3D images of body parts and objects [32].
Conversely, Virtual Reality (VR) is an entirely digital production (or reproduction) of an environment, including not only images but also sounds, that the user can interact with through dedicated equipment or his own body *(Abbas et al., 2023)*.

Despite considered to be born together with AR in 1968, the official term was only introduced by VPL Research founder Jaron Lanier in 1989, then associated with synonyms such as Artificial Reality, Cyberspace, Virtual Worlds and Virtual Environments *(Furht, 2008)*.

Depending on their intended function and the technology employed, VR might be classified as follows [33], [34]:

- **Non-immersive**: is a type of VR which allows the visualization of a virtually-built environment, potentially including sounds. Using a peripheric, such as a controller, the user interacts with the digital environment and causes effects on it. An example of non-immersive VR is a 360° interior design tool.
- **Semi-immersive** allows the user provided with devices (such as glasses or headsets) to visualize virtual worlds or features as a complement to the real world. It mostly focuses on the visual 3D side of VR, such as for interactive educational programmes and for flight simulators to train pilots.
- **Fully-immersive**: represents the highest available level of VR. The user is completely immersed in the virtual world and all the senses are involved: going beyond sight and hearing, it potentially involves touch and smell as well. Users can interact with the environment through dedicated tools, such as gloves and headsets. The 3D virtual space is realistic, and the user can move around and act as if the digital world has now become the real world. To complete the experience, additional equipment such as everyday objects and small means of transportation (i.e. bicycles, skateboards, etc.) can strategically be placed in the user' surroundings, so that the resulting feeling of the interaction is even more authentic.

Lastly, Mixed Reality was first defined by *Milgram & Kishino (1994)* and lays between AR and VR, allowing for interactions in both the physical and digital environments.

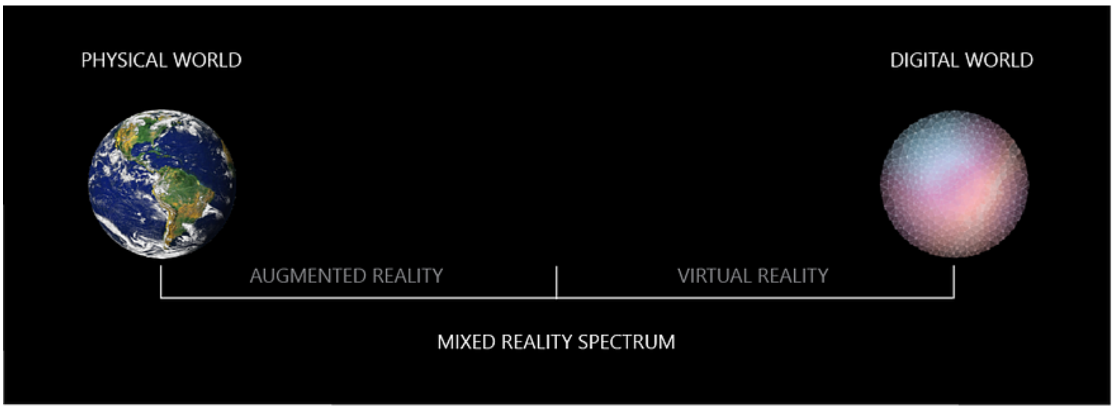

Figure 4. Spectrum of AR and VR [35]

AR finds multiple application and together with VR is being increasingly introduced in the videogame industry. However, not only gaming can benefit from this technology. In healthcare, VR will be used for surgery training, while VR can already be used to support doctors in diagnostic and surgery [36].

In healthcare supply chain, AR can be easily used on smartphones to display necessary information about drugs stock depending on the stage of the supply chain. For instance, within distributors warehouses key information might be arrival day and time, batch number, suppliers' details and destination customer, while within hospitals they may be expiry date, batch number and units left. AR can also be integrated in smart glasses, thus freeing operators' hands and providing guidelines, suggestions and warnings for specific tasks. It can drastically lower handling times and human errors, as it facilitates localization and signal irregularities *(Colabella et al., 2021).*

1.6.3 Advanced Automation

Advanced Automation is an I4.0 branch which includes those technologies, especially devices and equipment such as intelligent robots, with the aim to enhance activities and accompany workers in their daily tasks. Advanced Automation is particularly suitable for repetitive jobs: it allows workers to focus on tasks requiring a more elevated skillset and being relieved from more physically intense ones, while companies can cut costs, boost precision and time management. Its use is wide within the whole supply chain, notably for manufacturing and warehouse management [37].

Cobots (acronym for "Collaborative Robots") represent the most emblematic realization of Advanced Automation. Traditional robots were originally designed to substitute human tasks without interacting with operators and used to be separated by fences and barriers to protect humans from interaction with them (as it could be harmful). Instead, Cobots are defined "intelligent robots" and their purpose is to complement human activity; they are equipped with modern technology and sensors to detect the operator, interacting with him within his working space and preventing potential damaging actions [38].

In warehouse management, AMR (Autonomous Mobile Robots) today represent the evolution of AGV (Automated Guided Vehicles). The latters, already introduced in the past decades even before the concept of I4.0, are vehicles suitable for carrying goods over a predefined path and without an operator; the formers do not have to follow a specific route, instead their advanced sensors allow independent and free movement thanks to real time data collection and analysis, so that they can avoid collision with obstacles within the working area (e.g. operators, other vehicles, racks, etc) [39].

Drones can as well be included, as they can play a pivotal role in logistics, by delivering goods to remote areas or in the occurrence of major force phenomenon, or to simply fill the transportation gaps of existing and established systems.

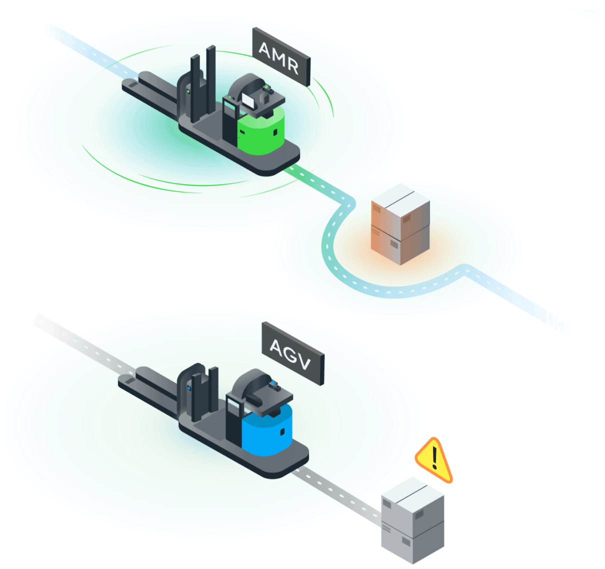

Figure 5. Representation of the major conceptual difference between AMRs and AGVs [40]

Within healthcare providers, cobots can assist medical staff in moving necessary tools to different rooms and unit, but also support surgeons for improved precision and higher success rate and in rehabilitation [41]. In healthcare supply chain, automated vehicles can aid in warehouse management for products with particular requirements (e.g. low temperature environment, chemical hazard). In addition, drones can support transportation of sanitary products to remote areas and between facilities. UNICEF distinguishes two logistic approaches for drones: delivery, which can be both one-way and reverse, is especially useful for drugs, vaccines, blood and tools; instead, pick-up, can be used for medical samples, wastage and documents transportation [42].

1.6.4 Cloud Computing

P. Mell and T. Grance, from National Institute of Standards and Technology (NIST), provided in 2011 a comprehensive description for cloud computing as an arrangement to providing network access to a set of authorized entities (i.e. devices, servers, applications, etc). Its founding characteristics are (*Mell, Grance, 2011)*:

- **On-demand self-service**, as human providers and administrators are not needed to the user to consult the network;
- **Broad network access**, as networks are standard and can be accessed by a large variety of devices;
- **Resource pooling**, as physical resources are used for multiple users at the same time yet maintaining the privacy of their online activity and information;
- **Rapid elasticity**, as resources are allocated to users when needed and can be moved among users to promptly respond to requests;
- **Measured service**, as use of and access to resources can be monitored to provide transparency to both users and providers.

Moreover, multiple models for Cloud Computing are available, depending on the users' needs. Despite new ones are emerging, the three most common are [43]:

- **SaaS (Software as a Service)**, which grants the user to access applications sourced by the provider through a dedicated interface (i.e. app, client or browser) while data is kept completely online and secured rather than stored on the users' devices, thus easily accessible from different devices through authentication;
- **IaaS (Infrastructure as a Service)**, which provides the consumer the cloud infrastructure to run chosen software, thus only providing IT physical resources;
- **PaaS (Platform as a Service)**, which permits the users to deploy services such as applications created with the provider's tools, so that control can be exerted only over the software and its configuration.

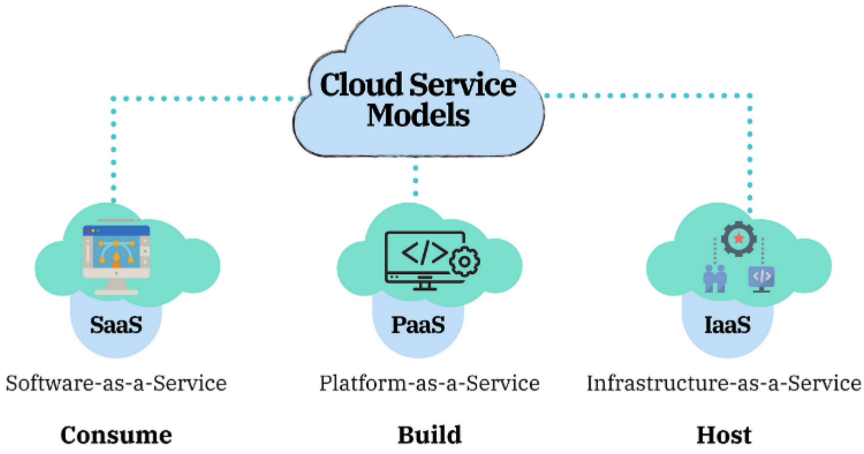

Figure 6. Cloud computing service models: SaaS, IaaS and PaaS [44]

Lastly, a third categorization can be done considering cloud's deployment model *(Rashid, Chaturvedi, 2019)*:

- **Private cloud**, designed to be used by a single entity (i.e. corporation, organization) and for its divisions (i.e. corporate departments, business units, subsidiaries) which maintain control over the cloud;
- **Community cloud**, when the infrastructure is dedicated to a set of users or organizations sharing some common features and is ruled and supervised by one of them;
- **Public cloud**, for the provider to grant the service to multiple users at the same time, while retaining ownership of the infrastructure;
- **Hybrid cloud**, when the whole infrastructure is composed by multiple of the above-mentioned models which maintain their features yet have some degree of communication allowing for data sharing.

Therefore, Cloud Computing serves as a basis for connectivity between application and consequently data collection and sharing. Adopting Cloud Computing has become increasingly vital for companies, as some IT services can be externalized for reasonable fees and thus results lower in costs, but better support and portability. It also allows companies to focus on core competencies rather than on IT resources, as development costs and efforts become minimal, and the necessary platforms are already designed by the provider and running successfully.

Cloud computing represents a precious solution to multiple problems within healthcare. First, data generated in the industry is constantly increasing and includes a wide range of information that have to be safely stored to grant privacy integrity and reliability (e.g. patients' data, diagnostic and test results, disease and research databases, etc). Cloud provides remote access to healthcare platforms for medical staff, thus fostering instant information and telemedicine, the newborn practice of online medicine (e.g. consultation of vital signs, prescriptions and historical patient data; access to online databases for research) which also promotes interaction among professionals to generate more accurate treatment plans [45].

1.6.5 Internet of Things

"Internet of Things" (IoT) was first introduced in 1999 by Kevin Ashton *(Mouha, 2021)*. As an engineer at Procter & Gamble he steered the implementation of Radio Frequency Identification (RFID) chips to monitor goods' status all along distribution. IoT includes a set of technologies and devices, specifically sensors and software, with the aim to grab information from the real world and turn it into data to eventually obtain insights and develop analyses. Therefore, Internet of Things refers to the ability to create a network of connection among physical entities that would be independent otherwise, allowing them to communicate through a dedicated infrastructure *(Granell et al., 2019).*
McKinsey lists some important features of IoT: hyper-connection, integration, security and trust, intelligence, mobile and hyper-personalization. IoT provides an environment for multiple devices to interact using different network standards and systems and adaptable to users' needs both in terms of data security and personalization [46].

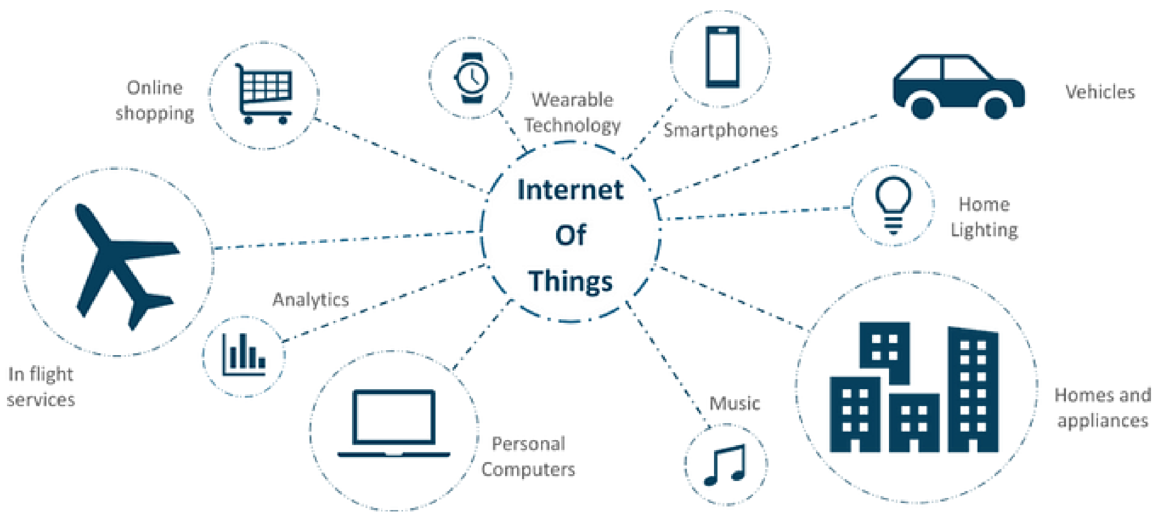

Figure 7. Map of some of the main applications for IoT [47]

IoT applications span in many sectors, from automotive to smart homes, from manufacturing to agriculture, from healthcare to logistics.

In automotive, IoT assists the autonomous driving function, but also in predictive maintenance for components and connectivity with external devices. Instead, security and energy efficiency and appliances automation can transform a traditional house into a smart home.

Manufacturing can be profoundly enhanced by the adoption of IoT to refine quality control processes, predict equipment failures and provide a safer environment for workers (e.g. by using wearable devices). In agriculture and farming, IoT is used to monitor crops and ensure the right environmental conditions are maintained for animals, for instance allowing for parameters regulation in watering and temperature control within farms *(Malik et al., 2021).*

Specifically in healthcare, devices are used to connect patients to medical staff and enable continuous monitoring of vital signs and symptoms, avoiding unnecessary tests and speeding up the diagnosis and hospitalization processes [48]. Wearable instruments, such as smartwatches, are also able to detect some basic vital signs and are usually complemented by a more appealing design, as the ultimate use is for personal interest. However, they bring some valuable functionalities: for example, an instantaneous emergency call can be addressed to authorities in the occurrence of accidents or strokes, without the user intervention and only considering data gathered and processed by the device.

Logistics can greatly be improved with cold chain monitoring and shipment tracking by using temperature-humidity sensors and RFID tags, allowing for continuous supervision over the transportation phase and help designing better solutions for supply chain management. Such sensors also assist in inventory automation and optimization, but as well in patients tracking by providing them seamless care and safer conditions [49].

1.6.6 Big Data Analytics

Big Data is the designated term for extensive type and quantity of data that can be obtained, especially by organizations, and subsequently analysed for tailored purposes. Thus, Big Data Analytics (BDA) pertains the processing of Big Data with the final objective to identify possible correlations and patterns that might help driving more informed and accurate decisions [50]. However, before analysing data it is necessary to turn them from unstructured to structured, meaning a standardized form such as numbers and texts.

In particular, Big Data is characterized by 5Vs *(Hiba et al., 2015; Ishwarappa & Anuradha, 2015; Keskar et al., 2020)*:

- **Volume** describes the massive quantity of data used for conducting following analyses. Owing to the widespread use of devices and new technologies, the volume of data available for collection has increased at a significant pace in the last few years, creating the need for more advanced data processing and storage tools to handle it effectively.
- **Velocity** describes the rate for data creation, collection and processing. Given the increased rate at which data is generated, systems must be able as well to quickly collect, process and analyse it to provide insightful information and steer the decision-making process.
- **Variety** refers to the different formats and categories of big data. Relational databases are examples of structured data, XML files are semi-structured data and media are unstructured data that lacks a defined structure.
- **Value** is the capacity of data to yield significant insights and promote well-informed decisions. However, intrinsic value in Big Data is time consuming to yield as the other V's considerably overcomplicate the whole course.
- **Veracity** pertains the accuracy and dependability of data. Data might be incomplete and inconsistent as a result of voluntary or involuntary causes. Data quality assures reliability of information deducted from data and guarantees more precise results.

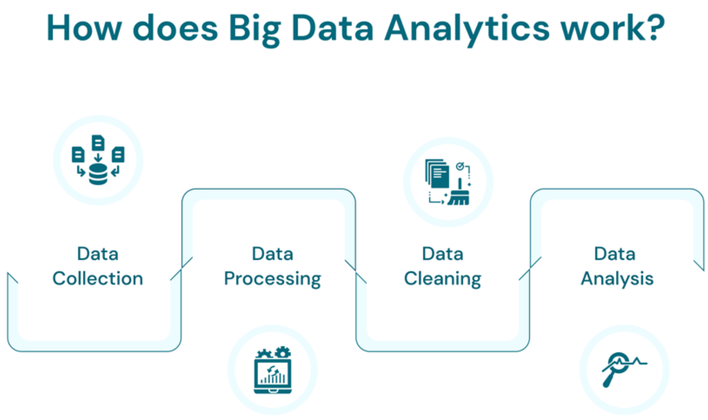

Figure 8. Representation of Big Data path towards usable information [51]

In healthcare, the main application for BDA is to be used to provide tailored services and care to patients, moving towards the so-called "personalized medicine", a medical model which aims to create decisions and medicines based on the individual; this upgrade can be integrated within Electronic Health Records (EHR) of patients to obtain support for future decisions. Big Data can be obtained through real time monitoring of patients, allowing to store a huge number of parameters, later analysed to make better and more precise choices of treatments and medicines to use. Within hospitals, BDA can help trace past patients' demand and predict incoming flows, thus permitting an improved resource management for both staff, available beds and medical equipment (*Bhatia & Mittal, 2019b*).

BDA offers a wide selection of benefits in healthcare, especially concerning diagnostics and prevention. Nevertheless, its advantages extend in the healthcare supply chain particularly regarding risk management (e.g. scenario forecasts and evaluation of risks based on events history), analysis of logistical matters (e.g. obtain more accurate ETA and lead time based on past shipments; predict customers' reorder times by previous ones) and analysis of suppliers' performance to identify areas of improvement *(Nargundkar & Kulkarni, 2019).*

1.6.7 Additive Manufacturing

Additive Manufacturing (AM) is a manufacturing process which aims at creating a product by adding material until the item reaches its final shape, in contrast with traditional (or subtractive) manufacturing techniques *(Bigliardi et al., 2024)*. Despite being associated with 3D printing, the two concepts are quite different. While in 3D printing the material is required to be added layer-by-layer, in AM addition can take place with other techniques. Though, the most common method still remain layer-by-layer and 3D printing can be considered as part of the process of Additive Manufacturing, which not only includes the manufacturing phase, but also the model design, quality check and post production and identifies larger scale production. [52].
AM is considered to be first introduced by Dr. Hideo Kodama in the early 1980s who developed the first AM related patent; subsequently, within the following decades, many inventors developed AM techniques and improved the overall methodology *(Fidan et al., 2023).*
Within AM, seven production techniques can be identified [53], [54], [55]:

- **Binder Jetting**: a binding material is deposited onto a powder bed and binds together the powder particles. The procedure is repeated for the following layers, until the final shape is obtained. Then, the semi-finished item undergoes a post-production phase to obtain a compact and smooth finished good.
- **Directed Energy Deposition**: a energy or heat source is used to melt powder or wire of raw material, commonly metal, which is deposited layer-by-layer following a CAD model. Particularly suitable for repairing and addition of small features to existing pieces, its most spread declinations are Laser Beam Melting and Electron Beam Melting, respectively employing lasers and beams as energy sources.
- **Material Extrusion:** thermoplastic material, a special type of polymer that becomes easily pliable at high temperatures, is fed into the machine and then pushed through a heated nozzle which causes it to melt. It is subsequently deposited on the print bed which lowers for each layer. Melted material binds with the adjacent layers and defines the final object. As final steps, the product is cleaned and post-processed for a smoother surface and remove debris. Fused Deposition Modelling, or FDM, is the most used among Material Extrusion processes.
- **Material Jetting:** drops of photopolymer resin are deposited on the print platform and a UV light source facilitates its solidification. The platform is then lowered by the thickness of one layer and the following is deposited on the previous one, until completion.

- **Powder Bed Fusion:** thin layers of powder are distributed on the platform and subsequently an energy source, for instance in the form of laser or electron beams, is used to heat power until melting. Steps are repeated for all the layers until the final product is obtained. Post processing can then help smoothen surfaces, while support removal is not needed as the object is laid in the powder. Types of Powder Bed Fusion are distinguished based on the energy source and are: Direct Metal Laser Sintering (DMLS), Electronic Beam Melting (EBM), Multijet Fusion, Selective Heat Sintering (SHS), Selective Laser Melting (SLM) and Selective Laser Sintering (SLS).
- **Sheet Lamination:** a sheet of material is positioned on the working area and an adhesive material is interposed between two layers. A heated roller is used to compact the layers, while a laser cuts the desired shape for the sheet. At completion, possibly a 3d complex object is obtained.
- **Vat Photopolymerization:** a moving platform is positioned inside a container filled with photosensitive liquid material. By using a thin UV beam, material hit by the light solidifies; the platform is being lowered and another layer of material is deposited to repeat the process. Stereolithography (SLA) is probably the most popular process of all the mentioned categories.

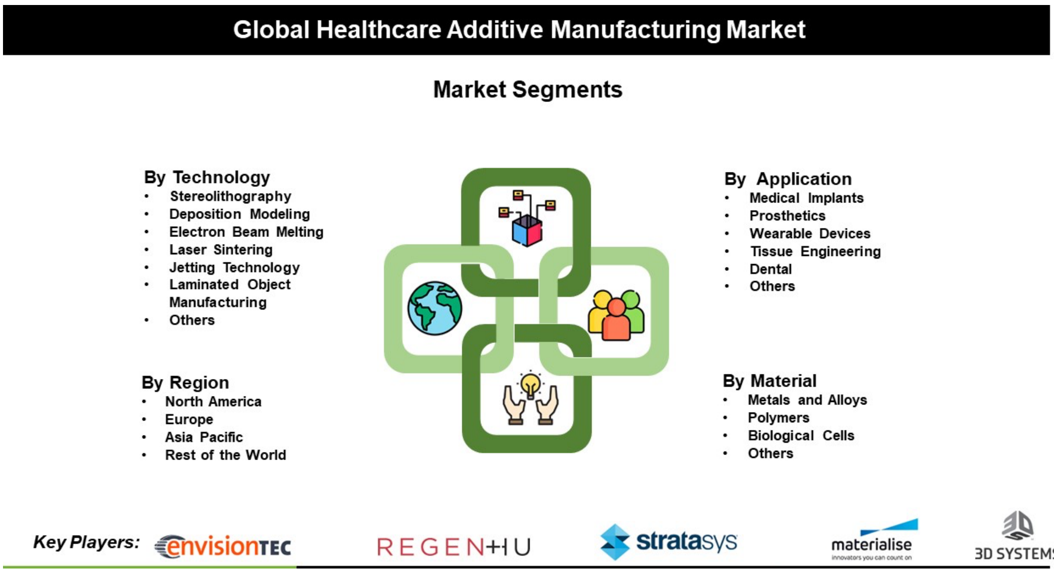

Figure 9. Market segments of AM: by technology, by application, by region, by material [56]

Additive Manufacturing in healthcare is contributing to personalized medicine. Multiple categories of finished products can be created with AM: implants, prosthetics, replicas of body parts for research and training and medical tools (e.g. for rehabilitation purposes). Various materials are suitable for sanitary 3D printed products, but metal and plastics are by far the most used, even though new materials are continuously added for improved performances [57].

1.6.8 Blockchain

Blockchain is defined as an approach to store transactions taking place among peers in a network in the form of a database. It is widely known as the founding technology for cryptocurrencies, non-fungible tokens (NFTs) and their exchange system, but its scope is continuously expanding to other applications [58].

Blockchain's main features are [59]:

- **Immutability and security**: transactions can't be reversed once officially registered and each attempt to change information requires a new transaction stating the request. Thus, data can't be altered in secrecy and its security is guaranteed. Time stamps are associated to each transaction, ensuring data is correctly stored and allowing for a transaction history to be created.
- **Decentralization and transparency**: control over transactions is shifted from a central authority to the peers' network. Complete transparency of data allows to create a secure environment without the need of a formal authority and prevent frauds, as well some peers to exert control on others.
- **Anonymity**: users have the right to remain unknown to other users, ensuring their privacy when recording transactions. However, a significant drawback is the potential rise of criminal activity within the blockchain, given mutual secrecy.

Four pillars of blockchain technology can be as well identified [60]:

- **Consensus**, as transactions only occur when approved by the majority of peers in the reference network. This feature grants a barrier-free environment for interested participants and transparency.
- **Smart Contracts** requires participants in the network must be checked and certified in order to take part to transactions approval.
- **Ledger** is a register containing the whole structure and history of transactions within the networks is created.
- **Cryptography** to ensure all information in the network and register is and remains uncorrupted, granting access to valid users only.

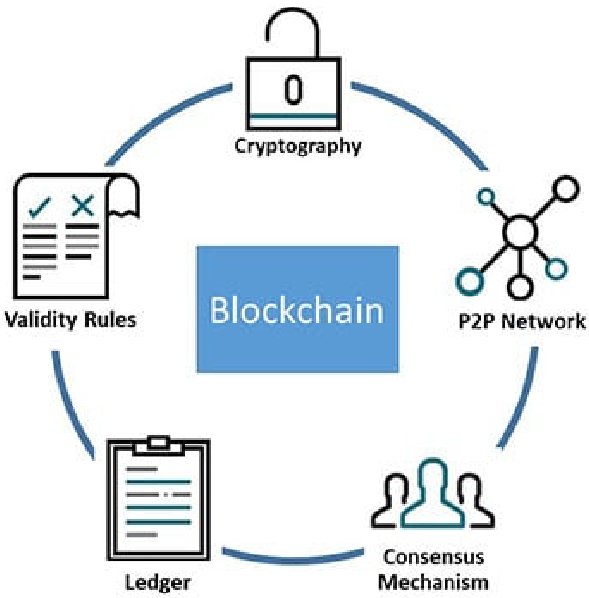

Figure 10. Elements of Blockchain [61]

While Blockchain in the healthcare industry is mainly a matter of patients' data governance and privacy, and as such lag behind other sectors for its implementation *(Tripathi et al., 2023)*, its main advantage in HSC is surely the increased traceability and transparency of goods all along the chain. Each movement and exchange is recorded as a transaction in the ledger and serves to establish a safe origin of medical items. Hence, patients only have access to authentic products which have not been counterfeited in any way: indeed, blockchain decentralized mechanism grants recorded data can't be altered and manipulated. Consequently, quality checks become automatic and require less human intervention and expenditure [62].

Chapter 2. Methodology

Chapter 2 explores the methods used to gather data on the theme of emerging I4.0 technologies in HSC. To this end, some real-world examples of their integration are reported to provide insights into the potential of such technologies. Moreover, interviews with HSC professionals are conducted taking into account strict ethical standards.

2.1 Research Approach

The research was carried out by using a qualitative approach to explore at a high level the HSC and digital technologies that might possibly improve it in the short and long term. The employed methodology can provide some key considerations as well as suggestions for future research: despite the mentioned technologies are at different stages of development and implementation, they are overall not near the mature phase and their market is expected to grow in the next few years [63].

Qualitative research leverages its exploratory nature to gain deeper knowledge of the HSC, and its existing problems and thus identify variables that might be and become relevant for studying them. It can better capture complexities that are difficult to represent through structured data, such as human behaviors and dynamics, and foster further inquiry as complexities unfold. Representation of the human component, for instance through interviews and surveys, is essential to not only rely on numbers but include nuances of specific situations and experiences in the field *(Dixit et al., 2019)*.

2.2 Data type and collection

Information used in the thesis was obtained by the analysis of other studies, articles and websites, meaning it was collected by scholars and authors and was later reused to address the set research questions. Secondary data is the term used to refer to such sources and identify data that is not directly gathered by the author of the study. Despite being a cheaper and time-saving alternative to primary data, its validity can sometimes be contested. For instance, it may contain undetected errors (e.g. in the collection or analysis phase), be inaccurate, and generalization might be unfeasible. On the other hand, sources may be precise and provide a reliable baseline for future research. For this reason, it is crucial to complement secondary data with primary data so as not to exclusively rely on third-party resources and to add further insights to the outcome *(Perez Sindin, 2017)*.

Primary data collected for this thesis is in the form of interviews. Specifically, interviewees were selected, and a semi-structured approach was used in order to gather relatively coherent responses. Yet, this structure allowed some degree of freedom to steer the conversation toward the preferred direction if needed, depending on the interviewee's experience and flow of ideas. This method is particularly suitable for gaining deeper knowledge about some concepts and topics mentioned by the interviewee when replying to the original set of questions, as it enables the interviewer with more flexibility, while still providing fixed guidance [64] *(Raworth et al., 2019)*.

2.3 Case Studies

In the first part of this chapter, selected case studies are outlined with the aim of answering the research questions. Particularly, a case study is a research method characterized by the examination of a specific phenomenon that takes place in the real world, considering its surrounding environment as fundamental to grasping the results *(Zainal, 2007)*. Its use is tied to the possibility that the reported scenario can be replicated or avoided in analogous contexts, depending on the need. It is especially beneficial when the phenomenon's boundaries are intertwined with the context, and the researcher has minimal control over events and their development, contributing to their unbiased observation *(Yin, 2003)*. For I4.0 integration within the HSC, case studies enable an appropriate comprehension of parties' interactions and innovations by exploring actual scenarios.

Case studies are an important component in the exploration of emerging or less explored fields, as they allow the formulation of hypotheses and the development of new theories *(Eisenhardt, 1989)*. Generally, they provide detailed data that might be overlooked in ordinary quantitative research, capturing organizational processes' and even behaviors' nuances. In the context of Industry 4.0 and healthcare supply chains, where processes and technology continue to evolve, case studies represent some empirical findings that address existing research gaps with the purpose of overcoming and solving them *(Cannas et al., 2023)*.

One of the key advantages of case studies is that they can provide a rich and balanced image of complex problems. They enable researchers to examine in detail specific circumstances, offering tangible results that may not only build up further theoretical understanding but also steer applications in similar contexts *(Crowe et al., 2011).* This type of analysis is particularly valuable in fields characterized by intricate processes and stakeholder relationships.

Case studies might allow to see processes and challenges unfold over time, and thus, provide a perception of the real dynamics of change and development within an organization or entity *(Yin, 2003).* This temporal aspect is critical in studying the adoption of I4.0 technologies in the HSC since it emphasizes the real situation of development and possibly the impact. Factors such as geographical location, time horizon, economic availability, geopolitical scenario and many others can greatly influence results in both a positive and negative way. Though, analysis of this kind can still provide general guidelines to develop tailored solutions, foster amelioration and a basic knowledge to build on for further improvement *(Birkel, 2019).*

While being effective, case studies are not without limitations. One of the main concerns is the potential "researcher bias", owing to which personal opinions and preferences might influence data gathering and analysis *(Yin, 2003).* Said subjectivity can affect the study's validity and reliability. Furthermore, whereas case studies surely offer detailed insights, the extent to which these are transferable to other contexts may be quite limited. This restriction is especially crucial in domains where circumstances differ considerably across various settings.

For instance, in a study of the application of I4.0 technology in HSC, researchers may choose examples that are representative of common applications in order to gain a deeper understanding of common barriers, challenges, but also successes derived from their integration. Conversely, examination of unusual or extreme examples may yield insightful information on atypical applications or potential drawbacks, to avoid or minimize future mistakes and aid in designing the best adoption strategies. The theoretical and purposeful selection of cases needs to be justified and is an important aspect of the case study, making it methodologically stronger *(Dźwigoł, 2020).*

To this end, research can involve not only case studies, but rather a combination of data collection methods, such as interviews, focus groups, direct or indirect observations, documentary analysis, and questionnaires *(Payne et al., 2007).*

Specifically, within the theme of I4.0 and HSC, case study research is applicable. The integration of advanced technologies into HSC is a complex process with many influencing factors, including but not limited to organizational culture, existing technology infrastructure, stage of development, regulatory environment, and workforce skills. Case studies allow for a closer look at these variables in their real-world circumstances, providing perspective on the barriers, challenges, and following benefits.

2.3.1 Justifying the use of Case Studies

Using case studies can provide an examination of how digital solutions are being implemented within HSC, ensuring that the evidence gathered is both extensive and relevant. The approach allows for the synthesis of information drawn from diverse sources but focuses on the company's official websites, which helps to bridge theoretical insights with practical applications which center on real scenarios.

One of the main limitations is the potential bias introduced by depending primarily on published online data from company websites and related sources. This reliance may not capture the full spectrum of experiences or emerging practices in the field; however, it provides real pieces of evidence about industry trends and their current state.

In particular, the use of case studies aims to provide a cross-case analysis, which is a scientific approach to research and evaluate systems change *(Lee & Chavis, 2012)*. This methodology enables an in-depth examination of similar issues and challenges across multiple cases, enhancing the robustness of findings *(Yin, 2003)*. Though common in qualitative-based disciplines such as social and political sciences, the cross-case methodology is also becoming valuable for innovation-related matters as it strives for comparison and generalizability.

2.3.2 Sources Selection

The search strategy used a variety of sources to ensure the assessment's width, reliability, and novelty:

- Company Websites, such as technology providers and companies in the HSC, healthcare institutions, and logistics operators involved in the transportation of medical supplies that are currently implementing I4.0 solutions. These sites mostly displayed successful case studies and product pages describing companies' experience in digitalization and how it positively influenced performances.
- Blogs and Press Releases, such as technical blogs and press releases were used to report on the latest news and current projects. These sources gave the latest information on pilot programs, partnerships, and new solutions launched in the market.
- Technology and Industry-specific Portals, which were helpful in finding companies that are undertaking digital transformation of their HSC. These portals typically have innovation stories, interviews with industry leaders, and also feature emerging trends.

2.3.3 Criteria for Case Studies Selection

The collection of case studies has been divided into two sections, the former dealing with Industry 4.0 digital technologies in the Healthcare Supply Chain, the latter including examples of Industry 4.0 digital technologies in other sectors. The reason behind this choice is to display not only the average level of adoption in the HSC compared to other sectors, but also to provide inspiration for advancements in the HSC. Specifically, the case studies referring to the HSC have been further split into three categories: manufacturers, distributors and logistic carriers, and healthcare providers. The distinction aims to identify the key actors in the HSC (*Betcheva et al., 2021)* managing the three types of flows, and as such, to showcase how technologies are employed at different stages of the chain with the purpose to upgrade it. The selected cases attempt to encompass multiple of the analyzed technologies (e.g. AI, Big Data Analytics, Cloud Computing and IoT), offering a variety of perspectives on the real state of evolution of the HSC. Moreover, industry leaders are on average more experienced in technological advancements compared to small and medium enterprises, owing to higher fund allocation for digital transition and R&D, but also to their organizational structure which includes teams explicitly in charge of encouraging, directing and managing the changeover.

The criteria for selecting cases are explained below, considering the second category serves as a benchmark for the application of some of the technologies in other industries.

Inclusion Criteria:

- Sources must directly discuss the application of Industry 4.0 technologies (e.g., AI, IoT, Blockchain, AR/VR, Cloud Computing) within the healthcare industry operations.
- Case studies must refer to the time frame 2018-2024. Industry 4.0 is recognized as a phenomenon that started approximately in 2011, thus the choice aims to gather quite recent information without extremely hindering possible matches by further narrowing the period.
- Considering healthcare in Europe is mainly public [65] and thus its mechanisms are similar among countries, the companies selected for the purpose of this study operate in the European territory but weren't necessarily founded in Europe. The reason for this is to gather the widest examples that currently are applied (or might be) in the European HSC. Moreover, revenues for the mentioned companies exceed €10 billion. The importance of choosing big companies arises from their influence in the industry and in setting industry standards, as well as their continuous innovation through massive investments in R&D [66]. Their constant partnership with startups, research institutes, governments, and other companies shows how innovation thrives through collaboration and building on shared knowledge. Furthermore, with access to a big pool of data, such companies lead the way in terms of advancements in fields such as predictive analytics, real-time monitoring, and automation. Concerning the selected healthcare providers, revenue was not taken into account, rather national-wide relevance was considered.

Exclusion Criteria:

- Any material that does not address these technologies within the context of healthcare logistics, such as those focused solely on other industries or unrelated topics, is omitted (unless purposely for the second case studies' category).
- Any material that does address healthcare but solely not operations-wise (e.g. Use of AI for diagnostic; use of IoT and Big Data to monitor and analyze vital signs).

2.3.4 Search Strategy

The search strategy employs a broad range of keywords and phrases tailored to the topic. An extensive search is conducted across the mentioned sources to ensure up-to-date information and examples of successful implementation as a result. Generally, cases were found through the combined use of many keywords:

- A technology, such as "Artificial Intelligence", "Internet of Things", "Advanced Automation", etc., or the abbreviation, if recognizable ("AI", "IoT", rather than "AA" which is less widely known and used).
- A noun or verb recognizing the state of the said technology, such as "adoption" or "adopted", "implementation" or "implemented", "integration" or integrated", etc.
- The context needed to set boundaries to the research, such as "Healthcare Supply Chain", "Healthcare Logistics", "Healthcare Operations", except examples from other industries.
- Boolean operators to combine the three components in a unique research query. For this purpose, the operator "AND" was the most effective, yet also "~" to search for a word and its synonyms, and "« »" to obtain an exact match (including the order of the keywords).

Examples of the resulting query would be "«AI application healthcare logistics»", "Internet of Things AND integration AND healthcare supply chain" and "Advanced Automation implementation AND healthcare supply chain".

The research strategy was carried out by undertaking a first round of search, using the keywords to make an initial selection. However, following this first research, the results proved to be insufficiently precise and required further refinement. Despite the inclusion of the mentioned keywords in the search queries, many of the identified articles only referenced these terms superficially (e.g. short references to innovations in HSC) while centering on unrelated topics, eventually resulting in a lack of relevant data. Thus an exploratory screening of the content of such articles allowed to further refine the selection and led to obtaining the real-world examples suiting the needs of the research.

2.4 Interviews

The section presents two interviews with Supply Chain experts who are currently working or have past job positions related to the HSC specifically. The interviewees are guided by a set of questions to discuss their experience with digital technologies in HSC, challenges, and opportunities. The interviews aim to provide further information on the topic to complement case studies.

2.4.1 Interviews in Qualitative Research

According to *Rabionet (2011),* framing a qualitative interview is a long process that includes several steps: starting from the type of interview to be chosen, the researcher should then outline the ethical issues and standards (such as confidentiality and informed consent), then define the interview structure and conclude with analyses and summary of the results as a consequence of the interview itself. *Karatsareas (2022)* also explains the need for equilibrium between structure and flexibility in semi-structured interviews, as it allows the participants to both provide in-depth information and express their thoughts freely without being confined to rigid question formats, thus praising this kind of interview for qualitative research. On the other hand, *Bogner & Landrock (2016)* point out that biases might emerge during the interview, namely acquiescence, social desirability, and moderate or extreme response biases, which may be particularly complex to recognize and must be countered as much as possible to render the data credible and reliable. Lastly, *Adams (2015)* also emphasizes the importance of the interviewer's expertise, preparation, and flexibility, highlighting the cruciality of having a friendly yet formal demeanor to facilitate open responses. These frameworks and guidelines overall informed the conduct and structure of the interviews employed in this research, maintaining methodological rigor while enabling an examination of the participants' views.

The combination of cases and interviews is crucial as it allows to broaden the vision on the matter and grasp experiences and opinions on specific occurrences in the industry. While the case studies may report a quantitative evaluation of the results obtained, the interviews aim to enrich the discussion with subjective details and dynamics of the events *(Öberg, 2016).*

2.4.2 Interviews General Structure

To prepare the semi-structured interview, the set of questions was deducted from the research questions. This process aimed to investigate the core inquiries of the thesis and create a guide for the interviewer to receive precious details about personal experiences in the field.

The interviews were designed considering a few key categories of questions:

- **Interviewees' background**: exploring it is significant to tie their technical responses to the overall context, allowing the researcher to interpret the data properly. Background questions typically revolve around demographics and other personal or professional experiences that might be relevant to the purpose of the research. Firstly, adding such an opening serves as an "ice-breaker", in order for the interviewee to become used to the interchange methods and feel at ease and relaxed, thus possibly leading to a more natural exchange *(Ranney et al., 2018).* Secondly, it may facilitate the classification of the responses according to any of the details provided (e.g. job role, years of experience, etc.).

- **Core Questions**: include all the primary questions directly addressing the research objectives. Core questions should be open-ended to encourage detailed responses and should align with the key themes of the study. *Ruslin et al. (2022)* emphasizes that in semi-structured interviews, this section acts as a framework that ensures consistency and comparability across many interviews. The questions should be phrased with neutral and natural language to avoid leading participants toward a specific response and influence results.

- **Potential Follow-Up Questions**: help explore unexpected or insightful responses that might emerge during the interview. They allow the participant to clarify vague, incomplete, or particularly relevant answers, investigate their underlying reasons and opinions, and adapt the conversation to obtain a unique point of view. Follow-up questions are essential in qualitative research because of the potential adaptability and level of detail that the interviewee might not obtain otherwise [67].

- **Final considerations and conclusion**: ending the interview on a positive yet respectful note is precious to facilitate future exchanges and reduce the risk of interviewees' concerned remarks. This section is an opportunity for the participant to add any final thoughts before parting ways and may include a summary of the key points discussed, as well as a thank-you statement to express appreciation for the time, effort, and insights provided [68]. According to *Castillo-Montoya (2016),* a proper closure also helps maintain ethical standards by ensuring participants leave the interview feeling both valued and heard.

2.4.3 Interviews Method

The technique chosen to select the interviewees for this research is known as Snowball Sampling (SS). Being a type of non-probability sampling, it is used in qualitative research to study particularly hard-to-reach populations *(Berndt, 2020).* In SS, participants bring in the project possible leads and future participants by contacting their relative acquaintances, thus creating the so-called "snowball" effect that allows researchers to find suitable profiles otherwise difficult to discover. Especially useful for the study of marginalized groups, this approach is also employed when conventional sampling methods do not work or become arduous to apply. The approach is cost and time efficient as participants become active components of the recruitment process. Not only that, but it can also establish a shared trust since new members are recommended by a common acquaintance and are more willing to reach out to the researcher and cooperate [69]. However, one of the main drawbacks of SS is its propensity to selection bias, because participants tend to suggest participants having kindred backgrounds, which in turn leads to less heterogeneous samples. Lastly, it can lead to the over-sampling of certain subgroups, hence diminishing the final effectiveness and diversity of the sampling process *(Atkinson & Flint, 2001).*

2.4.4 Interviews Questions

Castillo-Montoya (2016) developed a framework for designing interviews, known as Interview Protocol Refinement (IPR), whose first phase aims to verify the coherence between the interview and research questions. To this end, creating a matrix that establishes a direct connection between them is particularly helpful in ensuring the alignment between the study objectives and the data collection methods. The mapping of research and interview questions makes qualitative research more valid and reliable because it ensures all pertinent topics are covered. Hence, this phase prevents collected data from becoming scattered since each interview question will contribute to addressing the research objectives. The matrix shows any gaps in coverage, which encourages rework.

The interview questions were categorized into four main topics: professional background, technological awareness and their projected impact in HSC, benefits of digital technologies in HSC, and adoption barriers of technologies in HSC. Such thematic grouping is a common practice as it allows including all the necessary questions in the process of interviewing and participants to better structure their responses. The first section aims to place participants' knowledge within the context of the HSC specifically, supporting their insights with their relevant past experience in the field. The second category deals with participants' understanding of I4.0 digital technologies and their perceived impact on HSC processes, tackling the first research question. Similarly, the third and fourth sections try to determine the advantages of such innovations to HSC and express common challenges and obstacles in adopting digital technologies in the HSC.

The division is shown in the table on the following page (Table 1), highlighting the correspondence.

	Background information	**R1**. Which Industry 4.0 technologies are creating a bigger impact in the enhancement of the healthcare supply chain?	**R2**. Which benefits do Industry 4.0 digital technologies bring to the healthcare supply chain?	**R3**. What are the main barriers slowing the adoption of digital technologies in the healthcare supply chain?
Could you illustrate your professional background and your overall experience in Supply Chain, as well as your relationship with the Healthcare Supply Chain specifically?	x			
What do you think about when talking about Industry 4.0 and digital technologies, and which technologies in particular can you think of?		x		
Have you ever been involved in projects concerning Industry 4.0 digital technologies? If yes, could you describe what these projects were about and the results you obtained? Can you already see the benefits?		x	x	
Did you encounter any challenges when integrating this new tool or technology, at the company, department or team level? If yes, can you explain which ones?				x
Based on your previous experience too, what do you think are the benefits of adopting digital technologies in the supply chain, especially in healthcare?			x	
Which technologies do you think will be the most impactful in HSC?		x		
How do you perceive the short-term future, regarding technologies integration in HSC? What do you see coming and what do you think won't happen?		x	x	
Can you think about some trends that in your opinion will be widespread in the next years, in terms of technologies?		x		
What is a fundamental requirement for the adoption of digital technologies in the HSC?				x

Table 1. Alignment between research questions and interview questions.

2.4.5 Selection of Interviewees

Using the SS technique, participants were recruited through a network of professionals. Beginning with existing contacts in the HSC and logistics industry, interviewees were eventually referred. Similarly, online professional networks such as LinkedIn proved to be highly effective in revealing and verifying individuals with specialized expertise, given the possibility to make targeted searches by fields like job title, industry, and qualifications.

In order to provide relevance to the study, criteria to establish the desired professional background were defined beforehand. Moreover, supply chain research entails inputs from the professionals involved in several areas of the industry because they have a direct yet different influence on the way digital solutions are adopted.

The criteria used to select participants were intended to offer experiences diversity and are reported below:

- **Experience in SC and HSC**: a professional background in Supply Chain, though with a primary focus on healthcare, either with a permanent professional role or as active involvement in HSC projects. They might have worked for employers in adjacent and pertinent industries (e.g. chemical, transport and logistic, consulting with a focus on HSC).

- **Minimum experience:** the candidates are required to have a minimum of 8 years of work experience, to establish they have a good grasp of both supply chain practices and the increasing importance of digital technologies at the company level.

- **I4.0 experience in the HSC**: the participant should have gained experience in one or more projects concerning the adoption, integration, or management of I4.0 digital technologies in the HSC.

- **International work experience**: to gain diverse perspectives on the digital transformation of HSC, interviewees must have worked in at least two European countries.

- **Varied employer**: participants must not have the same current or past employers as other interviewees so that a good mix of approaches and projects is gathered.

- **Availability and willingness**: interviewees must be ready to participate in the interview process and share their experiences and opinions.

2.4.6 Ethical standards for interviews

Mirza et al. (2023) list the fundamental ethical principles to consider in data collection through interaction with interviewees and surveyed subjects. In particular:

- **Ethic of consent**: individuals involved in the research must be treated equally, with respect and trust, regardless of their characteristics (such as age, sex, race, religion, or lifestyle). Individuals must be treated fairly and with dignity, recognizing their rights and differences. Communication should be allowed in an agreed language they speak fluently and in a safe environment.
- **Relationship with participants and conflict of interest**: boundaries must be maintained or established between the interviewers and interviewees and personal relationships must not prevent unbiased response collection and elaboration.
- **Informed consent**: participants must be fully aware of the use of their contribution to the study and agree to conditions prior to the data collection. Their disagreement should either lead to the modification of some cited conditions or to not take part to the research. Data cannot be gathered without them being notified about means and purposes of the study, as well as any external party which might have access to their data. Participants' presence is completely voluntary and, as such, they have the right to withdraw at any time from the research.
- **Confidentiality and anonymity**: participants have the right to keep anonymity. This must be agreed before data collection. Moreover, material such as recordings, videos and notes must be kept in a secured storage in order to grant high privacy levels.
- **Reporting back to participants**: interviewees should be updated about the ongoing study and receive a copy of their material to check their response has not been altered. They also have the right to reach out to the interviewer for any feedback and further modifications if needed.
- **Issues of translation**: some concepts expressed in the interviewees chosen language might be reported differently when translated to the research's official language, thus the translation phase must be carried out carefully to avoid misinterpretations and translation biases.

2.5 Findings in Case Studies

2.5.1 Industry 4.0 digital technologies in the Healthcare Supply Chain

In the paragraph are included some real-world applications of the digital technologies in the HSC, divided in three categories as the most relevant actors within the HSC: manufacturers, distributors and logistics carriers, and healthcare providers. As these actors cover a significant portion of all interactions and flows in the HSC, the integration of digital technologies in their everyday businesses is particularly relevant to represent the benefits obtained by their adoption. This categorization aims to include multiple points of view within the industry to widen the opportunities that digital technologies might offer. The players in the industry are relevant, as companies chosen in the first two categories are among the leaders in the sector [70] [71]; the manufacturers have a strong propensity for innovation [72], while the distributors and logistics carriers have dedicated branches of the company for healthcare products' supply.

Manufacturers

a) Pfizer Inc. and AI-based tools

Pfizer Inc. is an American pharmaceutical company among the worldwide biggest and begun its massive digital transition process for the adoption of new technologies back in 2019. By the time Covid-19 hit and became a widespread issue in 2020, Pfizer had already established its own roadmap to integrate cutting-edge innovations within its corporate activities. For instance, both Artificial Intelligence and Machine Learning tools were deployed and used to assist in data analysis of vaccine's trials, while data sharing through a cloud platform allowed the majority of laboratory-monitoring activities to be conducted on remote, hence ensuring processes continuity despite the pandemic restrictions and obstacles to traditional work practices. On the production side, the company managed to develop a comprehensive overview of the manufacturing system among many of its plants, which was again paired with AI for predicting maintenance of manufacturing machines and facilities, and demand, consequently allowing to adjust internal and external operations. IoT technology was also helpful in the remote monitoring, as sensors' detections could assure goods to be transported respecting strict temperature and humidity requirements with a high degree of precision [73].

b) Merck KGaA and BrightLab™

Merck KGaA is considered to be the oldest chemical and pharmaceutical company in the world and one of the largest by revenues. Merck has recently introduced BrightLab™, a cloud-based solution for researchers launched during 2020 pandemic with the specific purpose to tackle inventory management issues and nurture connections among scientists to stimulate research advancements. Given the steadily growing amount of data to be processed and stored, the introduction of BrightLab™ at Merck also facilitated connectivity with lab instruments through IoT, sensors and data loggers. Contrary to the past, data is now automatically gathered without the need for physical intervention of technicians and lab experts, therefore accelerating lab activities and ensuring data protection and privacy by granting confidential access credentials to workers in charge and providing Secure Sockets Layer (SSL) encryption systems. Ultimately, BrightLab™ allows accredited users to browse across multiple Merck's inventories and sites, including features such as reorder near out-of-stock products and create a knowledge repository for documents and projects in order to improve consultation of existing sources for laboratories experts and scientists [74] [75].

Distributors and logistic carriers

a) UPS Healthcare and UPS Supply Chain Symphony®

United Parcel Service (UPS) is the major worldwide company for parcel delivery founded in 1907 in Georgia (US). After the acquisition of several distribution companies specialized in healthcare products handling, it opened its own branch UPS Healthcare in 2020 to provide better services to medical companies given the effects of Covid-19 disruption on the whole supply chain industry. UPS Healthcare now keeps acquiring related businesses to enhance its dedication to the medical industry. Its services now range from inventory management to cold chain logistics and the disposal of 1.6 million square-meters of Good Manufacturing Practice (GMP) and Good Distribution Practice (GDP)-compliant warehouses.

At the end of 2023, UPS has launched UPS Supply Chain Symphony®, a cloud-based platform for management of data coming from multiple stakeholders and systems along the supply chain, which allows customers and suppliers to constantly monitor their logistic metrics and shipments status, but also to receive tailored aid for the demand planning and forecasting. Easily integrated in the UPS Healthcare environment, the platform is designed to be intuitive and accessible, providing interactive dashboards to monitor every stage of the supply chain and merging services previously independent one from the other and taking place offline or by e-mail, such as Shipping Services (i.e. parcels delivery request), Logistics & Distribution (i.e. warehousing, transportation and returns services), Freight Forwarding (i.e. get freight quoting and booking shipping slots), Customs Brokerage (i.e. dealing with trade regulations and help customers in managing diverse laws restrictions among countries), Suppliers Management and Express Critical® Services (i.e. faster delivery service for urgent need of medical goods) [76][77].

b) Maersk and Captain Peter

Maersk is a leading logistic carrier founded in 1904 in Svendborg (Denmark), having its major businesses in supply chain and warehousing. The company provides a temperature mapping system to monitor transportation conditions and ensure compliance with medicine requirements. Maersk launched a remote container management platform called "Captain Peter" to assure shipments' temperature and humidity is kept within recommended ranges. The platform also includes an automatic notifications system triggered in case freight conditions abruptly change or are not suitable anymore for medical goods safe use. Maersk also provides its clients with pharmaceutical-only warehouses, facilities specifically destined to storage of medical items. Such deposits are ruled on a first-expiry-first-out principle and are always supervised by experienced pharmacists and Maersk's Quality Management System [78] [79].

Healthcare Providers

a) National Health Service Scotland, Global Healthcare Exchange and Kortical Ltd

The National Health Service (NHS) is the British publicly funded healthcare service and represents the state-wide healthcare system in England, Scotland and Wales.

Specifically in Scotland, NHS has been introducing Global Healthcare Exchange (GHX) services to automatize inventory management within some national facilities. GHX is a renowned company for technological related services in the healthcare industry, founded in 2000 as a consortium of healthcare players.

At NHS Scotland, the adoption of such technologies resulted in several improvements nationwide. For instance, pilot healthcare provider managed to save approximately 40 hours and 5,000£ per month on creating new purchase orders from online catalogues; automatic data analysis and reporting features allowed to free time for upper-level workers to focus on managerial tasks rather than mechanical ones; stock count was digitised and became continuous over time, permitting further savings and allowing real-time tracking for an increased transparency and safety compliance. Automatization of these processes not only led to lower inventory and ordering costs, but also to dedicate more time to core functions and especially to medical care, drastically decreasing human errors in stock management and wastage of medical products otherwise due to lack of time and dedication to these activities. After the success of the pilot project, GHX services are planned to be extended to the whole Scottish healthcare infrastructure to enhance its patient care [80].

NHS is also partnering with Kortical Ltd., an AI Cloud platforms company with the aim to support the implementation of Artificial Intelligence and Machine Learning based tools within organizations. The cooperation targets an efficient blood supply chain, which is and the AI-based software provides support in demand planning, leading to up to 54% decrease in expired blood products and eliminating Ad Hoc transportation for such urgent goods. NHS Blood and Transplant branch data was gathered, then used to train the algorithm and to start forecasting demand for the existing 40 types of bloods supplied to the healthcare system, which include platelets, plasma and AB0-labeled bloods. The tool was able to identify at the source the patterns of blood donors' appointments and create an accurate forecast of the supplies that will be available. Blood demand was then predicted among the 15 hubs involved, while a dedicated application was built to host dashboards for inventory and demand related KPIs, trends and projections. Moreover, the system allowed to significantly diminish the Ad Hoc transportation costs, which refers to peculiar logistics solutions for items to be delivered in a short time frame and at a specific time [81]. Kortical states that such costs were eliminated within six months from the beginning of the project, still maintaining the previous high rate of on-time delivery. Ultimately, the newly launched platform allowed to discontinue the old methods used for demand prediction, especially a complex network of spreadsheets [82].

b) Zuyderland Hospital and Mediaan Conclusion

Zuyderland Hospital is a medical center located in the Limburg region (Netherlands) and created in 2015 by the fusion of two previously existing hospitals: Atrium Medical Center Parkstad and Orbis Medical and Care Concern Sittard-Geleen. The facility counts almost 1000 beds and tens of thousands yearly admissions, making the beds and patients management system quite complex to run smoothly [83]. For this purpose, Zuyderland Hospital and Mediaan Conclusion launched a partnership for their experts to join forces and improve patients' logistics. Internal coordination is essential for the hospital to achieve and keep satisfactory care services, allocate medical staff effectively and anticipate future resource needs. Mediaan tailored software is equipped with predictive analysis algorithms conducted on historical data to anticipate incoming patient flows and to better schedule and manage goods, workforce, and facility's spaces. Moreover, computer simulations are constantly carried out to leverage the hospital's capacity and enhance interdepartmental flows, leading to a higher admission rate and service level. In order to obtain accurate results from such simulations, Mediaan Conclusion states the importance of gathering precise data from everyday operations and creating a high-quality database as the starting point for accurate analysis and predictions. When such simulations are being shared with the management and supply chain experts within the healthcare center, they are always accompanied by a certain degree of confidence, so that best and worst-case scenarios could be kept under careful consideration. Machine Learning is used in the process to help identify patterns in patient flows and relate them to external events, thus contributing to the instruction of the algorithm for enhanced future predictions [84].

2.5.2 Industry 4.0 digital technologies in other sectors

a) Hapag-Lloyd and intelligent automation

Hapag-Lloyd is an international shipping company, founded in Hamburg (Germany) in 1970. In 2022, its volumes reached 11.8 million TEU (20ft long containers), marking it as one of the biggest logistic carriers in the world. As such, the company aims at providing excellent service to customers, in a price aggressive market.

To keep being relevant and competitive in the next years, Hapag-Lloyd has been reinforcing its IT compartment and infrastructure, with the aim to digitalize all documents and procedures which are still often handled on paper and manually. In particular, the company has been investing in Robotic Process Automation (RPA) by partnering with SS&C Blue Prism to automatize key procedures and gaining precious results in approximately three years from the partnership launch. Hapag-Lloyd states that 40 to 60 workers were devoted to the elaboration of the shipping bills of lading, while RPA allowed them to now focus on other key tasks. Biggest benefits of RPA reported by the company have been time and monetary saving, estimating at 500,000 hours from the launch of the project, but a crucial component in such a successful case study is the mindset and cultural change the company embarked on.

Considering the increasing frequency of disruptive events, RPA has proved its efficacy in emergency management, assisting the company in rerouting and rescheduling tens of thousands of shipments within one to two business days. Lastly, RPA allowed Hapag-Lloyd to enhance invoice disputes management by automatically detecting key information in queries and addressing them to the right people, providing support in finding solutions as well [85].

b) Amazon launches Sequoia and Digit projects

Amazon, the US e-commerce, and digital services giant, has long invested in streamlining operations and continuous improvement of both its logistics and warehouse management. As such, more than 750.000 collaborative robots have been introduced within Amazon’s facilities around the world, with the aim to reduce physical burden on workers over repetitive and mechanical tasks. During the second half of 2023, “Sequoia”, pilot of a brand-new robotic system, was launched in the fulfilment centre in Houston (Texas, US).

Amazon declares that benefits arising from the adoption of these new robots is approximately a 25% faster order processing and 75%-time reduction in items identification and storage, allowing for overall acceleration of orders fulfilment and greater products availability and

turnover. Sequoia solution aids workers in their daily tasks and reduce needed effort in some strenuous ones to prevent injuries. For instance, after picking an order items, a specific robotic arm ("Sparrow") refills the corresponding tote, which is then ready for the next order.
Moreover, Amazon has introduced "Digit", a new bipedal robot able to work within human-designed working environments and suited for handling and picking operations [86].

c) Luxury leaders and the AURA Blockchain Consortium

In 2021, several luxury groups and individual brands joined forces to launch the Aura Blockchain Consortium, a non-profit entity with the aim to promote the introduction of blockchain technology at multiple points within the luxury industry. The Consortium can count on the effort of crucial players such as LVMH, Richemont and Prada Group to create a bigger impact with the initiative.
Blockchain in the luxury industry is becoming increasingly helpful to distinguish between original and counterfeited items, as a Digital Product Passport is released and updated to keep track of some fundamental features. For example, blockchain can assure origin, manufacturing, distribution and ownership, thus authenticity, claim and transferability are granted in the occurrence of resale [87].

In Table 2, the key concepts from the case studies above reported are presented, including both those for Healthcare Supply Chain and other industries.

Case study	Technology used	Outcomes
Pfizer Inc. and AI-based tools	AI/ML, Cloud, IoT	AI, Ml, Cloud and IoT led to optimize trial processes and results for vaccines development by granting remote lab monitoring and ensuring continuity of research. Pfizer also used them for predictive purposes (i.e. demand, maintenance) and to control and adjust temperature and humidity along the supply chain to ensure compliance to regulations.
Merck KGaA and BrightLab™	Cloud, IoT	The Cloud-based platform BrightLab™ improves inventory management and scientific collaboration by integrating data from warehouses and laboratories in multiple sites. It also aids in reordering near out-of-stock items and foster consultation of documents in an inclusive environment.
UPS Healthcare and UPS Supply Chain Symphony®	Cloud, IoT	UPS Healthcare was launched in the Covid era to better meet medical companies' supply chain needs. From 2023, the Cloud platform UPS Supply Chain Symphony® allows constant monitoring of goods and shipments and provides help in demand planning and forecasting. UPS can now grant an Express Critical Service for urgent medical supplies deliveries.
Maersk and Captain Peter	Cloud, IoT	Cloud platform Captain Peter, coupled with IoT, allowed to monitor and control transportation conditions. The system is linked to Maersk's warehouses dedicated to pharmaceutical supplies storage.
National Health Service Scotland, Global Healthcare Exchange and Kortical Ltd	AI, ML, Cloud	GHX partnership led the pilot provider to save 40 hours and £5,000 per month on purchase orders, enable real-time inventory monitoring and reduce storage costs, human errors and waste, allowing the provider to focus more on medical care efforts. Kortical Ltd partnership allowed to reduce expired blood products by 54% and eliminate ad-hoc transportation costs by improving their demand forecasting accuracy.
Zuyderland Hospital and Mediaan Conclusion	ML	Mediaan Conclusion's ML-based software improved the prediction of patient logistics by using historical data to anticipate future patient flows, thus allowing to optimize scheduling and management of resources. This led to a higher admission rate and service quality.
Hapag-Lloyd and intelligent automation	RPA	RPA led to: significant cost and time savings, by automating the shipment of bills of lading and freeing 40 to 60 dedicated workers; saving 500,000 hours of work just in 2023; rerouting of 50,000 shipments in 1-2 days; improve invoice management.
Amazon launches Sequoia and Digit projects	Advanced Automation	25% faster order processing and 75% reduction in item identification and storage time. Over 750,000 robots were deployed to improve efficiency and reduce workers fatigue and injuries in activities, such as handling and picking.
Luxury leaders and the AURA Blockchain Consortium	Blockchain	Successful partnership to ensure product traceability and authenticity through the creation of a digital product passport blockchain-based.

Table 2. Summary of the case studies.

2.6 Interviews Summary

The section presents two interviews with Supply Chain experts which are currently working or have past job positions in the Healthcare industry specifically. The interviewees are guided by a set of questions to discuss about their experience with digital technologies, challenges and opportunities. The interviews aim at providing further information on the benefits of technologies in the industry and a starting point for future research.

2.6.1 Interview 1

The first interview was held online, and the interviewee will be identified as "I1".

I1 is currently located in Italy and is employed at a medical products company as a Supply Chain Director. I1 has previously worked in international settings at a pharmaceutical company as a Manager. I1 now oversees processes such those of inventory management, demand forecasting and reverse logistics for defectives at a regional level (Europe). I1 is also specialized in analyzing cold chain performances, while in the past also dealt with the creation of models to enhance overall stock management for the chemical industry.

I1 has recent and ongoing experience with digital technologies applied to the HSC. Together with the team and external experts, I1 has taken part to the launch of a Machine Learning-based software for corporate use. Its aim is to provide support in setting optimal target stock levels for the company biggest warehouses in the region and in demand forecasting to better match the incoming request of products coming from healthcare providers. The software is supposed to benefit both the workers (by assisting them in easier, but time-consuming tasks), and the company, by providing long-term economic advantage in terms of inventory and transportation savings. However, among the two, the biggest impact for the team is expected in the daily activities, as the software should relieve some of the work pressure to allow supply chain employees to focus on tasks requiring higher-end skills.

The project was fully launched almost one year ago, thus I1 remarks how it still is in an initial phase. During its simulation, the software performed quite well and set great expectations for the implementation. Nonetheless, I1 encountered several difficulties in the transition from purely traditional instruments to the integration of the new advanced software. Though, trial results are still far from being reached, hopefully estimating to achieve full potential in the near future.

Based on personal experience and contacts with other professionals in Supply Chain, I1 remarks as the digital transition in the field is still at an embryonal phase and only a minority of companies is managing to upgrade their current systems. I1 states that in Italy only one third of companies approximately should be actively involved in digitally-enhancing projects. The greater part is stuck with traditional means or evaluating whether engaging into transition or not and at different levels of involvement.

I1 underlines as the company was willing to invest in technological projects and thus, financial barriers were not a matter in this case. However, workers exerted some resistance as they needed further training to make the tool work smoothly in the daily tasks; thus, the bigger challenge I1 encountered was about change management and how to properly integrate training into the already tight daily schedule. I1 stresses the importance of a well-established training and change management policy to steer and support improvements within the company, as this would significantly reduce employees' resistance and rather show them opportunities. As well, transparency is fundamental all along the process to avoid unnecessary discontent. Lastly, I1 makes it clear that the newly launched software is not designed to substitute humans, but to provide aid in repetitive and time-consuming activities. In particular, simulations showed that the most efficient implementation scenario resulted to be given by joining human and technological components. Economic benefits are not really tangible yet, but I1 foresees the main impact will be visible within the team dynamics. On the other hand, the launch of the software was fairly welcomed by local supply chain teams too, distributed among many business units. They embraced the adoption of an even working tool, though are still being introduced to it.

I1 was not directly involved in launching other projects for technological integration, but is aware some companies are trying to establish blockchain within their infrastructure. However, for supply chain specifically, I1 believes Artificial Intelligence is going to be the most disruptive among I4.0 technologies. The activities AI could provide support for are multiple: not only it would allow to save a lot of time in mechanical tasks (otherwise completed manually or on Excel or other obsolete software), but also possibly reduce human errors and provide useful insights by the analysis of data. I1 remarks its relevance in demand and trends forecasting, and its aid in managing and writing complex documents, for instance supported by AI assistant or other similar features able to help for employees' requests.

As a conclusion, the following table (Table 3) presents the key concepts from the first interview.

Concept	Takeaway
Impact on daily operations and savings	The ML-based software is expected to relieve pressure on the Supply Chain team in their tasks, allowing for more time to be dedicated to higher level analysis and strategic activities tasks. Economic benefits are expected in inventory and transportation mainly.
Barriers to adoption	Resistance within the Supply Chain team, even though not excessive, was the biggest barrier to adoption. Conversely, the company had the financial means to support the software deployment. Lack of uniformity among business units is requiring more time for the alignment of competencies and equipment needed.
Current situation of HSC	A minority of companies have fully adopted some digital technologies, while the remaining majority is still working on the integration or have yet to start.
Most impacting technology	I1 believes AI is going to be the most disruptive technology in Supply Chain and Healthcare, owing to its numerous applications.
Role of technology	Technology is aimed as a support for humans rather than their substitution. Best results are achieved when human and technological skills are combined.

Table 3. Key concepts from Interview 1.

2.6.2 Interview 2

The second interview was held online too, and the interviewee will be identified as "I2".

I2 is currently located in Denmark. I2 is employed at a consulting firm as a Digital Transformation Manager and has previous experience at a logistics carrier company as Innovation Manager. I2 supervises multiple projects about implementing new technologies within companies and had the chance to personally verify the status of their integration among different industries. I2 has recently taken part to two similar projects in HSC. The projects were about the implementation of a cloud SCM tool, respectively for a pharmaceutical and a medical products company. I2 almost had experience with a pilot implementation of blockchain technology in HSC, but the project hasn't been launched in the end. In relation to blockchain, I2 states that its adoption is particularly fostered by some important luxury companies, as granting the origin of raw materials and manufacturing of final products is becoming crucial for customers' experience, as well as for resale and renting purposes. Similarly, I2 remarks as the biggest challenges in supply chains are transparency and data sharing. Companies are still not willing to share data with suppliers as it partially helps them keeping their competitive advantage; however, data exchange would greatly enhance demand forecasting tools, especially now that Machine Learning and big data are improving predictions' accuracy. In I2's experience, less than 10% of firms is actively interchanging data with other actors in the supply chain by providing them with full visibility, while the majority of players range from very limited visibility to completely lacking.

Referring to some previous assignments in Healthcare, I2 states that the companies which engaged in digital transformation projects to improve their supply chain by adopting cloud-based solutions managed to lower related costs by approximately 5%, but further optimization can still be pursued and would ideally lead to a total of 10 to 15% decrease.

However, I2 noticed a big shift in the digital transformation trend only after the pandemic: several companies are now using consulting services for this purpose, but many others even decided to internalize transition processes by creating ad-hoc departments or reinforcing IT and Supply Chain ones by hiring experts and ex-consultants.

Concerning the most impactful technologies, I2 believes AI is the most relevant, while blockchain still has a long way before being implemented at a global level and thus, does not expect a different situation for Healthcare. For I2, this is due to most firms rather insisting on Artificial Intelligence implementation, as benefits result not only in the supply chain area, but in many other branches, especially marketing, communication and human resources. Again, blockchain has been growing in the past few years, starting its rise just before Covid-19 hit. Though, the pandemic slowed the adoption due to its disruptive effects that forced companies to revolve to AI, also considering soon after ChatGPT and AI-based chatbots showed the massive impact they could bring with relatively low investments.

At last, as a significant barrier to blockchain adoption, I2 remarks its need for a complete infrastructure and openness mindset from participating firms, which is not yet achieved and will probably take 5 to 10 years more to be reached. Along with these, another critical barrier is related to data regulation: ownership, copyright, privacy and cybersecurity are key themes to be addressed before massive investments are made in blockchain and AI, as many companies are worried about potential misuse of data fed to such algorithms and tools. In I2's view, issues related to data regulation in Healthcare Supply Chain are going to complicate even more the use of technologies as patients' data protection is a core theme to be addressed.
To summarize, the following table (Table 4) presents the key concepts from the second interview.

Concepts	Takeaway
Issues in the industry	Transparency is one of the key issues in the industry. For instance, demand forecasting is quite inaccurate when actors are not willing to share crucial data.
Technologies and costs reduction in HSC	Companies adopting cloud-based solutions managed to reduce their costs by approximately 5%, and further improvement is to be expected up to 10-15% when their supply chain is optimized.
Digital Transformation and Covid-19	Most of the companies started their digital transition process during and after the pandemic, especially in fundamental industries such as Healthcare.
Data regulation in HSC	Some of the digital technologies' broad distribution, such as for the blockchain, is slowed down by lacking legal background for data treatment, especially concerning patients and their medical status.
Barriers to digital transformation	Lack of transparency, data regulation and privacy issues, and lack of platforms' uniformity slow down the transition.

Table 4. Key concepts from Interview 2.

2.7 Comparison of interviews and case studies findings

Despite the common thought, interviews and case studies confirm that the digital technologies' adoption is quite at the beginning. In healthcare, high costs of the patient care services often draw funds and prevent improvements in the supply chain aspect. As a consequence, healthcare providers' management insist on more tangible applications of technology within medical areas and tend to neglect the importance of streamlining supply chain. Moreover, as explained by Interviewee 1, the time needed to record visible benefits coming from technologies' implementation within companies can take up to several years, thus preventing other organizations from embarking in the transition process without actual results to justify further investments. Specifically, steadily evolving technologies originates the risk of investing in yet immature ones and restrain funds from developments perceived as more beneficial for ultimate customers.

However, for companies willing to fund the transition, the main barrier seems to be the shift in skills and the necessity to create a suitable culture of change which support employees with training and accompany them in the changeover. For this purpose, both interviewees suggested the relevance of involving experienced workforce coming from other companies and pair hirings with internal learning and development. Overall, results obtained from launching such technological projects are not easy to find and further feed the already existing lack of data sharing and cumulative knowledge on the matter.

The most promising emerging technology appear to be Artificial Intelligence, as its wide capabilities can support many roles in their daily activities. For instance, Supply Chain Analysts can be supported in data examination and trends spotting, while in the next steps Supply Chain and Warehouse Managers can be supported in the demand forecasting and inventory management practices; not only AI can provide assistance in supply chain specific tasks, but it can also help at managing documentation and facilitate contracts' understanding.

The main takeaways from both the case studies and the interviews are illustrated in the following table (Table 5).

Theme	Case Studies	Interviews
I4.0 digital technologies	• Real-world applications of AI, Big Data Analytics, Cloud Computing, Internet of Things and Blockchain.	• AI, Blockchain and Cloud are the most mentioned technologies. AI is regarded as the most revolutionary and flexible, followed by Cloud as essential technology nowadays and by Blockchain as promising for the future.
Benefits of I4.0 digital technologies in HSC	• Improvement in demand forecasting accuracy • Enabling of remote monitoring and efficient resources management, from manufacturers to healthcare providers • Improvement in inventory management • Cost savings and business continuity in the occurrence of pandemics and major disruptions • Enhanced and automatic disputes management • Real-time tracking, traceability and authenticity of goods from source to destination	• Reduction of human error • Improvement in efficiency and accuracy in demand forecasting and inventory management mostly • Support in repetitive tasks • Cost savings in transportation and inventory • Improvement of documents' management • Reduced working times for mechanical activities and analysis
Barriers and challenges for implementation	• Integration with existing infrastructure • Necessary skills of employees and consultants • Legal barriers (i.e. data regulations)	• Resistance to change and adoption within the Supply Chain teams • Fear of being replaced by technologies • Legal barriers for the widespread adoption of certain technologies (i.e. Blockchain, Cloud, AI)
Technologies and future	• Wider adoption of successful pilot projects • Reinforcement of companies 'infrastructures for increased flexibility, efficiency and resilience • More successful case studies on the use of Cloud, IoT and AI or ML	• AI and Cloud's broad adoption in the near future • Shift in the skills necessary to implement and manage technologies

Table 5. Comparison between takeaways of case studies and interviews.

Chapter 3. Conclusions

In this last part, the conclusions drawn from the previous chapters are presented. In light of the time frame of the thesis work and the range of data included, expressing some final considerations is particularly relevant to contextualize the obtained results. Along with them, the contributions and limitations of the study are discussed before providing suggestions for future research.

3.1 Overview of results

During the research has emerged that not all I4.0 technologies are expected to have the same impact on the future of supply chain, specifically in the healthcare industry. Most of such technologies are interdependent and designed to work properly when integrated altogether. IoT sensors create the bridge between physical and digital world by capturing information from the environment. Cloud Computing connects entities and provides them remote access, boosting cooperation. Furthermore, Big Data obtained from IoT devices and shared through Cloud platforms, is then stored into specific databases. Consequently, insights can be derived from analytics and can feed Artificial Intelligence algorithms to enhance further analysis, prediction and decision-making aid tools. Blockchain can then help securing gathered data, especially relating goods tracking and financial transactions. IoT and Big Data are also the basics for implementing Advanced Automation, which necessitates real time analysis of the surroundings to work properly. Lastly, Additive Manufacturing is impacting the healthcare industry as the future of personalised implants and prothesis rather than having direct effects on the HSC. This remarks the interconnection between such innovations and the importance of a joint integration in order to obtain the full set of advantages.

Among all of them, AI seems to be the most promising, as its benefits are so wide and already tangible to the collectivity, keeping the public interest high and encouraging companies to further invest in it.

Areas that benefit the introduction of digital techologies in the HSC are multiple, while their direct correlation emerged during the study is highlighted below in Table 6.

	Additive Manufac-turing	Advanced Automation	Artificial Intelligence	Augmented and Virtual Reality	Blockchain	Big Data Analytics	Cloud Computing	Internet of Things
Demand Forecasting and Planning			X			X	X	X
Inventory Management		X	X	X	X	X	X	X
Maintenance optimization		X	X	X		X		X
Cost reduction	X	X	X		X	X	X	X
Real-time visibility		X	X		X	X	X	X
Quality control	X	X	X	X	X	X		X
Operational efficiency	X	X	X	X	X	X	X	X

Table 6. Relationship between I4.0 digital technologies and their benefits.

Therefore, benefits can really be drawn only if an accurate implementation plan for these technologies is set up, fitting to healthcare requirements specific to geographic, economic and social contexts and building on the already existing knowledge base. Technologies overall increase product visibility along the chain and revealed to be helpful for safety reasons in particular, as integrity of medical goods and of manufacturing companies' practices can be recorded and certified, streamlining communication among interested stakeholders.

However, numerous barriers are significantly retarding the expansion of digital technologies to the whole HSC. By conducting the research, the difficulty in finding real-world examples targeting the HSC emphasized how the attention is currently centred on improving medical activities, such as diagnostics, surgery and preventive care through telemedicine and EHR analysis, rather than on the supply chain side. General realization of the importance of HSC improvements to grant high quality patients care is needed at managerial level and among shareholders for them to promote investments in the transition process of the HSC alongside the pure healthcare. More interest in the topic could lead to greater attention of the institutions and consequently start solving some legal barriers. For instance, the urge for a revision of the current limitations of the General Data Protection Regulation (GDPR) about data collection, transferability and the required security standards for data management is critical to pave the way for digitalization. To this end, engaging in more governmental discussions about data regulations, compliance and related relevant topics is compulsory.

3.2 Contribution of the study

The thesis has the purpose to address the potential applications of digital technologies to the HSC. The need to specifically focus on the healthcare industry stems from the pivotal role it had in the last few years in developing and providing vital medical supplies as the Covid-19 pandemic hit.
The structure of the healthcare sector is complex and includes flows of a large variety of medical goods, in addition to customers (i.e. patients), often making it difficult to adopt the same policies, software, processes, etc. HSC challenges should be addressed by targeting unique issues within healthcare (e.g. importance of timely delivery to guarantee emergency provisions; careful handling of delicate medical goods and equipment; elevate number of product categories and relative transportation conditions) and not only drawing from successful case studies from other sectors. The digital transformation has the prospective to significantly change the healthcare sector and ultimately provide more effective care to patients. However, a roadmap for their implementation should be defined and structured to meet specific requirements of the adopters, being pharmaceutical firms, cold chain specialized logistics carriers, distributors or healthcare centres.
This research contributes to fill the existing research gap on the matter, providing a guideline for involved actors on the multiple opportunities that technologies create, still fostering a critical evaluation of side effects, such as the managerial implications and the evolution of the required skills to deal with such transformation. Indeed, HSC transition towards I4.0 technologies is still far from its peak, but recent events forced all parties to engage in it, even though at a different pace.

3.3 Limitations of the study

The thesis has several limitations to be taken into account. As the digital technologies' landscape is evolving at a fast rate, especially as a result of the Covid-19 pandemic, future developments and outcomes might still differ from the conclusions expressed. The technologies highlighted in the thesis work are gradually being integrated in the daily and corporate life, gaining important shares of the companies' investments for the next few years. However, their current premature status does not allow to accurately forecast the economic benefits they could bring to the HSC. An increased interest in this matter could lead to a growing number of patents and papers for specific HSC applications, thus speeding up the transition process of the industry.

Indeed, secondary data included in the work does not encompass all existing findings on the theme, especially the most recent ones that still have not been documented or have not become public yet due to companies' competitive advantage-related reasons. Besides, the thesis addresses the theme of digital technologies in HSC, but purposely includes some insights from other industries.

Interviews also provide a direct example of the status of implementation of such technologies in certain companies, but results to be an incomplete picture as they do not represent the situation of all companies in the industry. However, they equipped the study with evidence of difficulties and advancements in the adoption, which should be extended to many other actors to gain a more accurate representation of the reality.

3.4 Further research

More efforts should be focused on the HSC specifically, as the current research is rather concentrated on the healthcare industry in general with little studies on its supply chain. Some areas of improvements of such technologies in the HSC might even still not being discovered or become evident, and thus may need further investigation as the development unfolds. Additionally, the initial upfront investments are quite demanding and hazardous, considering that benefits and regulations are not yet roundly defined. Consequently, further research should address the economic benefits digital technologies can effectively bring to the HSC and evaluate the best technologies in terms of performance improvements and costs. Not only, future studies could assess the effectiveness of a step-by-step rather than an immediate and full integration of technologies within and among organizations. To this end, specific analyses should be conducted to establish a ranking of the most suitable technologies to be adopted first and thus, define a customized path for digital transition. Considering the role of the different actors within the HSC is essential to give context to the individual technologies and select the ones generating superior value. However, their full potential within HSC would only come from the between the actors, to be achieved through a shared effort of the parties.

Aside from benefits, risks should be assessed as well. Digital technologies could lead to disruptions in the job market and to the mismatch between existing and needed skills for future workers, possibly causing serious unemployment consequences. As such innovations become widely accessible on the market, the shift of many tasks from being handled by humans before and by digital technologies now is taking place. Even though this near future is leading to the inevitable displacement of certain job positions, it is also creating room for more accurate, prompt, cost effective and flexible solutions. If not to this extreme level, the transition can lead to the creation of some new roles and the need to deal with technologies in the everyday working life. Employees are gradually called for the upgrade of their skillset to maintain their relevance in the job market, thus contributing to an overall sense of pressure for quickly adapting to the upcoming requests. For this reason, further investigations would be necessary to assess the shift in competencies in the HSC in order to create a favourable environment for the adoption of useful technologies and not let the industry lag behind even more.

Important consequencies arise from their use. Firstly, data safety and confidentiality require stricter regulations to prevent breaches, unauthorized accesses, and proper sanctions for misuse. In this direction, major efforts should be focused in designing laws and in traning societies about the correct approaches when dealing with data and technologies in the HSC. Secondly, given the current situation, biases are especially tangible when using AI. For this reason, attention should be paid to the impact such biases have on healthcare operators' decisions and to prevent distorted perceptions and analyses. For instance, further studies should evaluate the degree of accountability of decisions taken by AI compared to human ones, to correctly split responsibilities.

Technologies cannot be simply implemented depending on funds and availability of skilled experts, but has to be planned by detailing a roadmap suiting each actor's need. It should be based on its role within the HSC, the systems currently in use, the level of cooperation with other actors

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and the final objectives to be achieved. For example, to ensure a successful digitalization of healthcare providers, different considerations must be taken in comparison to manufacturers and a dedicated plan must be established to guarantee the gradual integration of the new tools within the entity.

Surely, technologies should be also assessed from a sustainability point of view. Route optimization, predictive maintenance, traceability of medical supplies from origin to end consumer, waste reduction are just a few examples of the potential environmental benefits deriving from their adoption. As a result of the ever more central matters of ESG, not only productivity and economic benefits should be considered. On the contrary, social and environmental themes should be given importance as well, allowing to reach a balanced and seamless transition.

Lastly, future research could provide a combination of industry-focused interviews and surveys to create a benchmark for HSC among geographic areas and key actors. Indeed, a wider number of interviewees and surveyed should be included. This would provide deeper knowledge of the current and expected situation of the digitalization of HSC, as its fragmentation and variety of healthcare provider typologies cannot be otherwise fairly represented. For this purpose, benchmarks should be carried out at national and regional level, or else between diverse healthcare organizational structures, to draw from both successful and unsuccessful experiences and facilitate the movement towards a digitalized HSC.

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Annex 1

Interview Structure

Professional background:

- Could you illustrate your professional background and your experience in Supply Chain, as well as your relationship with the Healthcare Supply Chain specifically?

Knowlegde about I4.0 digital technologies:

- What do you think of when talking about Industry 4.0 and digital technologies?
- Which technologies in particular can you think of?

Experience of the interviewee with I4.0 digital technologies:

- Have you ever been involved in projects concerning Industry 4.0 digital technologies?
- Could you describe what these projects were about?
- What were the results you obtained?
- What were the benefits?

Barriers and benefits of the adoption of I4.0 digital technologies:

- Did you encounter any barriers or challenges when integrating this new tool or technology, at the company, department or team level? If yes, can you explain which ones?
- What do you think are the benefits of adopting digital technologies in the supply chain, especially in healthcare?

Future of I 4.0 digital technologies in HSC:

- Which technologies do you believe will be the most impactful in HSC and why?
- How do you perceive the short-term future, regarding technologies integration in HSC? What do you see coming and what do you believe won't happen?
- What is a fundamental requirement for the adoption of digital technologies in the HSC?
- Can you think about some trends you might be perceiving now will be widespread in the next years?

Politecnico di Torino

Interview 1

Interviewer is identified as "I", while Interviewee as "I1".

I: Good morning and thank you for taking part to this interview today. As we agreed, the conversation will be transcribed automatically, and your identity is kept anonymous. To begin, could you illustrate your professional background and your overall experience in Supply Chain, as well as your relationship with the Healthcare Supply Chain specifically?

I1: *Sure, I'll start from my job then. As you know I'm based in Italy right now as my family resides here and I really wasn't a lover of the Northern European weather. So, my role at [medical products company] is Supply Chain Planning Director. I've been promoted a year ago and I joined as a manager. Basically, what I do is to oversee the globality of processes for inventory management, demand forecasting and reverse logistics for our defective products in Europe. For some countries, I'm supported by the local Supply Chain teams, as we can't manage all the information without having specialists on site at least in the biggest markets. Of course, when I say "I", I'm referring to my whole team, I'm not alone in doing all these tasks.*

I: Okay, and how many people are there in your team, to have an idea?

I1: So, *my team is of 4 people I'd say, me included, while the whole Supply Chain team is bigger than this. Roughly it should be between 8 and 10; I can't tell you precisely as I know some movements are happening right now in the department, but are not public yet.*

I: It is fine, thank you. Please you may continue where you left.

I1: *Okay, so before this current role I worked as Supply Chain Manager at [pharmaceutical company] for around four years and even before I had few years of experience at [chemical company] as a Specialist. I had some experience in analyzing cold chain performances for pharma and creating stock optimization models for the chemical one.*

I: Great, thank you. Could you specify the country where you worked in for the past employers?

I1: *When I was a Specialist I was working in Germany, while for the past job at [pharmaceutical company] I was located in Switzerland.*

I: Wow, this is really interesting. You had some wonderful opportunities.

I1: *Yes, I feel lucky I had the chance to have some experiences abroad, but after a few years I preferred coming back to Italy and spend more time with the family, you know. Plus, I like my job and the company and the team, so it's a win-win.*

I: Good. So, now I'd like to delve a bit in the Industry 4.0. To begin, could you tell me what do you think about when talking about Industry 4.0 and digital technologies, and which technologies in particular can you think of?

I1: *Yes, so I'd say that reminds me of the big technologies that we're all focused on right? For example, Artificial Intelligence and Blockchain, I think they're the most debated out there. I mean AI has exploded in the last few years and months, while Blockchain is not as much famous but sometimes you can hear about it when they talk about cryptocurrencies. Then, apart these two probably the Cloud, even though I think is a bit more established and accessible.*

I: And have you ever been involved in projects concerning Industry 4.0 digital technologies? If yes, could you describe what these projects were about and the results you obtained?

I1: *Sure! So this is why I said AI as a first thing. A couple years ago, so right after Covid, we deployed a Machine Learning-based software within [medical products company]. It took a lot of effort from our side and we had to ask for external support at [software company] as there were no direct experts in Machine Learning within the company, but the deployment was quite successful. I'd ask you to omit [software company] name as well, because we are still working with them, and the company doesn't want this kind of information to be communicated outside the organization.*

I: No problem at all, it will be removed from the transcription.

I1: *Thank you. Anyway, going back to where I left, I can say the software is useful for the purposes it was created for but I believe there's still room for improvement and that its full potential and benefits will be visible at least next year. The software basically helps us to, let's say, set optimal stock levels for our main warehouses and also to improve the activity of demand forecasting by* *making it more accurate. In this way we can better predict where our products will be needed and requested based on a more "intelligent" analysis of demand.*

I: This seems very interesting. So you said the software is not at its best yet, but can you already see the benefits?

I1: *Yes, as I said it's only been some months we really implemented it into our daily tasks, so we just have some partial results of the real benefits. I mean… It's a bit less than a year, yes. The first thing the team noticed was that less time was required to do some tasks that usually took a lot more. And we can easily analyze more data than before in a shorter time frame and with higher accuracy. I think it's important because the team now can focus on more "strategic" activities and yet obtain better results. So, again is a win win.*
One last thing I believe is important to mention is that the software doesn't have the purpose to substitute part of the team or everyone in it, at all. I'd say on the contrary, it's really helpful as a support, but not able to work independently. When we carried out the simulations, prior its launch, we tried oud different settings and scenarios and the combination of the team's efforts and the software revealed to be the most promising. On the economic side, of course we expect it to generate main savings in inventory as we can avoid unnecessary stock, and in transportation too. I have some rough numbers, but I'm not allowed to share them yet… I don't think the software will impact our team expenses overall, rather our routine.

I: Okay, no worries, thank you. So, this sounds like an ambitious project overall, but hopefully will lead to the results you all worked for and I wish you good luck for this.
Instead, moving on from the software and talking more about the environment you work in, did you encounter any challenges when integrating this new tool or technology, at the company, department or team level? If yes, can you explain which ones?

I1: *To be honest I don't recall encountering any particular challenge, except a little resistance on the team side for the adoption of the new advanced software. The company supported the project by investing in it and even though I wasn't in charge of managing the budget I never heard about relevant financial issues. Within the team instead, many colleagues were quite skeptical about it, but this is because it was about to change our daily approach, so it meant to learn how the software worked and everything. When we talked about it to other business units around the world, they* *were even more skeptical, but also happy we were working for a common tool. I can't blame them as similar tasks are carried out in very different way depending on the location, and we have a bit less than 20 business units. Some of us use Excel, while some others, and I'm referring to emerging countries especially, they do a lot of checks on obsolete software, even paper sometimes. I'm not talking about Supply Chain only, but several departments are in this situation, especially because we acquired some businesses lately that have diverse approaches and we're still trying to make everything work as a whole and provide them with the right basic tools and training. However, at a team level, some colleagues were kind of worried about fitting the training for the new software in the tight schedule. A couple people were already missing in the team due to maternity leaves, and the pressure to complete all the things was already higher than usual. I can also tell that deep down they were quite worried the program could lead to their layoff in a very near future, and this is why we stressed during all the process that it was not the company's intention.*

I: I get it. And based on your previous experience too, what do you think are the benefits of adopting digital technologies in the supply chain, especially in healthcare?

I1: *For sure there are many benefits. The first thing I can think of is the support it can give us for some repetitive tasks. In Healthcare, delivering some products can determine between life and death and so deliver in time is crucial. Moreover, AI in general is a powerful ally for analysis of huge databases and can help us reduce human error a lot. I'm looking forward to it, honestly.*

I: So which technologies do you think will be the most impactful in HSC?

I1*: I'd say again AI by far I believe is the most revolutionary for me. For sure is the one most companies are focusing on at the moment and wins quite easily on the other ones, in my opinion.*

I: And how do you perceive the short-term future, regarding technologies integration in HSC? What do you see coming and what do you think won't happen?

I1: *Honestly, I didn't have the chance to take part to other digitalization projects. Most of the things I heard about started after Covid. But I think at least for Supply Chain and Healthcare, AI will help us soon at managing thousands of different documents. We deal with so many people and parties and they are often quite long to read. So, I think some kind of function, like an AI assistant* *or similar, will help us to avoid reading everything many times and just grasp the needed information, as if you were asking an expert directly.*

I: Can you think about some trends that in your opinion will be widespread in the next years, in terms of technologies?

I1: *You mean if I know about some other company projects and technologies they are planning to invest in?*

I: Yes, emerging technologies or Industry 4.0 ones that you believe might become widespread in a few years.

I1: *I think out there opportunities are so many it's difficult to predict what will come in the next years. My only real experience with such technologies is this project I told you about, while other projects I was part of in the past weren't about the use of a new Industry 4.0 technology like Machine Learning or AI. I know some old colleagues are now working in other industries' Supply Chain and some of them are trying to explore blockchain. I think it would be interesting as well for Healthcare, but there's a long way to go in my opinion. Overall, supply chains still have a lot of work to do in terms of digital transition. Just a few companies are fully aware of the potential and are deploying digital technologies massively. When we thought about launching the software we also did some research about the current situation and I remember it turned out only one out of three companies were involved in some kind of improvement of their systems, so the majority was still using traditional software or maybe evaluating whether it's necessary to change something or not.*

I: One last question. You said the biggest barrier you encountered was some kind of resistance among your colleagues to accept the new software and, if I got it right, it included a sort of fear they had to be replaced by it in the coming future. Drawing from this experience, what is a fundamental requirement for the adoption of digital technologies in the HSC?

I1: Yes, as I said, since the beginning of the project we always stressed that the software was going to be a support rather than a replacement of people. But I get the fear they had, it's normal. One day you work on Excel and the day after AI becomes public, news say it will "steal" thousands of jobs and you then decide to launch a Machine Learning project. I believe that in our situation it *was fundamental the intervention of the training and change management team, because they helped in the transition and in designing the right path for the trainings. They understood the objective was to combine humans and technology and that it also was the approach providing greater value to the company, rather than a 100% human or 100% software scenario. So overall I'd say transparency is an essential requirement.*

Interview 2

Interviewer is identified as "I", while Interviewee as "I2".

I: Good afternoon and thank you for accepting my invite to this interview. As I told you, the interview will be automatically transcribed, while your identity will remain anonymous. If you don't have any concern, we can start.

I2: I'm happy to help and no concerns on my side.

I: Perfect. First of all, I'd start asking an overview of your professional background. Could you illustrate your experience in Supply Chain and your relationship with the Healthcare Supply Chain?

I2: Sure. I started as a Supply Chain Analyst and gained around 5 years of experience in a shipping company while in the south of France. Then I was promoted manager, but I was more interested in the innovative side rather than in the daily operational side, you know. I saw the everyday life of an Analyst and even though the promotion was inevitably leading to a change in my daily activities, I really wanted to do something different and try to bring some changes within the company. So with a bit of help and onboarding I entered the innovation team as Innovation Manager. Our purpose was to manage all initiatives related to new software and tools, be the sort of Program and Project Managers for ongoing innovation projects of any kind and continuously look for hints on the market of what could be useful to implement in the company. Anyway, now I moved on from the pure logistics and I'm a Digital Transformation Manager here in Denmark.

I: And you are working for a consulting company, is it correct?

I2: Yes, true. We're specialized in helping companies choose and implement digital solutions. Some of them are in the Supply Chain as well.

I: And can you highlight your link with Healthcare?

I2: You're right. I got lost saying about the innovation thing.

I: No problem at all.

I2: So recently I took part to a couple projects in the Healthcare Supply Chain. I guess we are going to discuss about them later, right?

I: Yes, we can talk about them later.

I2: Okay, perfect. So yes, two projects with the implementation of Cloud solutions. This is basically the very short version of the story. I don't want to anticipate your questions.

I: It's totally fine. I just wanted to quickly comment on your background and I have to admit it's a very interesting path. Anyway, going back to our topic, I'd like to ask you about Industry 4.0. So, what can you think of when talking about Industry 4.0 and digital technologies? And can you think of some of them specifically?

I2: With my job, I saw many of them applied to the corporate world. But for sure, AI and Blockchain are the first thing that come to my mind now. Then, I cited the Cloud and after it I'd go for the automatization side, like intelligent robots… Maybe some 3D printing too? Yes, in general my thoughts go to everything related to data and data analysis, virtualization and automatization.

I: Perfect, thank you. Have you ever been involved in projects concerning Industry 4.0 digital technologies in Supply Chain and specifically in Healthcare? Can you describe what these projects were about, as well the results and benefits you obtained?

I2: Sure. In 2023 I was about to get this possibly promising project for an Healthcare e-commerce that wanted to embark on the Blockchain journey. They wanted to make their Supply Chain transparent and become one of the firsts at doing it. But in the end we didn't start the project because of many reasons, first of all they were undergoing an internal crisis so it was better to wait rather than start such an important project for their relatively small reality. However, for this occasion I got to know about some interesting Blockchain projects out there and some of them are really cool, for example in luxury they're trying to create a big network for traceability and authenticity of materials and processes. I think this is soon becoming an added value for customers, because you can guarantee all the steps and even push it forward for sustainability, so you can use it for the resale. This way, people know whether the item you're selling is original or not. Interesting right?

I: Yes, I agree. Honestly I never heard much about Blockchain before this year. We mentioned this at school when talking about luxury companies, so I guess you refer to the partnership among the luxury giants?

I2: Yes, that's the one. So you already know about it.

I: Yes, yes. We had a lecturer at school this year to briefly present the project. But thank you for pointing it out. What about projects in Healthcare Supply Chain?

I2: Interesting! Well, I had a couple assignments in Healthcare time ago. One was for a pharma company, the other one for medical products, but both were about implementing a Cloud-based platform. For both of them, in the end we decided to adopt the same cloud SCM. I think Cloud is one of the most necessary upgrades for such companies so they can keep an eye on their supply chain. We managed to reduce their operating costs in their supply chain by 5% at first. Then with some more tuning and the deployment of the fully working platform reached a 15% reduction. This was for pharma. The other project achieved a milder result, I think it was around 11% reduction. But they were working on their supply chain too at the time so we had to wait for their upgrade for savings to be 13-14%.

I: Considering benefits overall, not just in terms of economic ones, can you provide some examples?

I2: Well, yes. In my opinion, they were able to level-up the coordination between business units and this helped a lot in the sales planning and to keep an eye on what the inventory situation was like. Data was easier to get without many steps like they used to until then. So this also saves time, and in some industries time is the key. Healthcare is one of them.

I: And at a broader level, what do you think are the benefits of adopting digital technologies in the supply chain, especially in healthcare?

I2: Taking as a starting point the project I told you about in pharma, when you get access to a lot more information and in faster way than you did before, you can change the way you manage your stock, all transportation and the manufacturing. So for example, you can avoid medicines to be produced in case warehouses already have enough stock, and on the opposite you can easily check *whether it's needed and you should start producing soon or not. Then some unexpected events happen… A pandemic, a war. Or more than one, sadly. And the entire supply chain goes into pieces. After what happened in 2020, it's necessary now to act and modernize the infrastructures to provide supplies in time. Sometimes it can make the difference for a patient's life.*

I: I agree with you in this.

I2: I mean, you can find mere economic reasons for adopting technologies, or just realize you're not serving a "normal" customer but saving his or her life. If you can invest in the diagnostics and vaccines, you should find room [for improvement] for supply chain sometimes too.

I: True. And this second reason is a good one to keep you motivated and be better than yesterday. What about the barriers and challenges instead? Did you encounter any when the platforms you mentioned before were launched in those companies? I'm referring to both internal and external ones.

I2: Of course there are so many barriers and limits to overcome. We talked about Blockchain, right? You see, Blockchain is the technology that should bring the real transparency to the supply chain. You cannot modify anything without peers to know it, every step is traced to the tiniest detail. Now, that is 100% transparency…ideal for the moment. We need to really want this transparency, it's not just about saying it to be more appealing in the eyes of customers. For this to happen and to make it widespread, I think 5 or 10 more years are needed. All the issues in cybersecurity… and data privacy is delicate, even more when dealing with medical information and some regulations are still not very clear. Plus, people are still worried their data is going to be used for other purposes rather than just for healthcare. We need to teach people how these technologies work, so they won't be as scared as they are: healthcare is essentially privacy. At least, supply chain wise I think the shift could be easier because Blockchain could significantly help in tracing defective batches and expired ones, or to authenticate the origin of the drug you're using. We're not there yet for a large scale. For so many companies, all the updates on their shipments takes place through e-mail. When the customers asked them where their container was, sometimes they came back to us asking updates on the shipment and when you have several clients it's a loss of time. So one barrier, except the legal ones I said earlier, in my opinion, is that there are so many different software and platforms available that it's difficult to integrate data in a single place and have *everything ready-for-use. Around one out of ten companies are providing a full visibility of the needed data to their partners in the supply chain. This should mean all the others only provide or have a partial visibility and even worse, not at all in some cases. Hopefully, with all these technologies at hand something can be done about it.*

I: Thank you. Then, which technologies do you believe will be the most impactful in HSC and why?

I2: I think AI is the most tangible one and we can already see its results or at least some of them. The good thing about it is that it's great at doing so many different activities I can't even mention them all. It needs to be refined, yes, but if we consider the huge steps it did in a couple years it's impressive. And within Supply Chain for sure can help for analysis and in a relative short time I believe it will be so much more powerful than today. I wished I had it in logistics a few years ago. And of course you can use it not only in supply chain but also for the creativity, so marketing and communication… I think they are going to use it a lot as well. Human resources, strategy… No other technology is so flexible and promising at the moment. Especially with ChatGPT, almost everyone uses it now at work when they need help. It's easy because you can just ask questions and it answers on some matters you might need support in. Or also, the AI chatbots on websites. They're quite easy and relatively cheap to develop. They're intuitive and so customers prefer to ask them rather than wait to ask the support service. Anyway, after AI I'd go for Blockchain. I hope to have a good project with it soon, but for Healthcare I don't really know whether they are doing something or not. For sure is not mainstream like AI right now, so it might take time for a wider adoption.

I: Thank you. Can you think about some trends you might be perceiving now will be widespread in the next years?

I2: We already noticed a big change after Covid-19. You know it even better than me probably. We were forced to go online even more than we used to and you lived it during the university, right?

I: Yes, a tough period indeed.

I2: Exactly. So as you can imagine the "before and after" the pandemic reports two completely different situations. Companies, independently from their size, were really scared of losing money *and going bankrupt because of it. Some of them were less lucky than others and unfortunately did go bankrupt. So a trend right now is to reinforce the IT and technological part in general; it could be hiring consultants or proposing tons of courses to the employees so they can improve their IT skills. And in Supply Chain as well, you remember the disruption all around the world so it's normal that everyone now wants better and stronger systems to be prepared for similar situations. Hopefully not another pandemic, but you never know.*

I: Yes, this makes sense. Thank you again. Then, how do you perceive the short-term future, regarding technologies integration in HSC? What do you see coming and what do you believe won't happen?

I2: I believe it's something that will happen gradually, you know. We can't really force it, neither hope for another pandemic to shake everything again. It's reasonable to expect some of the technologies we mentioned will have more success than others or simply will be adopted sooner, easier, with less investments and overall efforts. It's important to address the new skills that will become necessary to manage the new digital ecosystems, but this is not only for healthcare. For the near future I see AI and Cloud being the protagonists. That said, Healthcare and its Supply Chain are very complex and sensitive data is a tough area to manage, so I don't think we are seeing AI disrupting them so soon. Let's not forget though that these technologies are moving fast and it's difficult to predict their growth.

I: I know we are running out of time, so I'm just asking this last question: what is a fundamental requirement for the adoption of such digital technologies in the HSC?

I2: Supply Chain investments should be prioritized. Trainings for employees need to be, so they could become comfortable at using the new platforms and smoothly transition to AI-powered ones. And more uniformity in the chosen tools, for an easier integration.