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Universal Manufacturing – a Review of Enterprise Interoperability

MASTER'S THESIS IN
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Abstract

Enterprise systems collaboration across different domains has become increasingly pervasive. Along with the transformation of the manufacturing and service industry towards globalisation, an opportunity to reconsider the architecture of future enterprises has emerged. This research work stems from the innovative concept of Universal Manufacturing (UM). Following the description of UM enablers, the main paradigm's properties, including Interoperability, are presented. Interoperability in industry 4.0 refers to collaborations between physical and virtual entities, producers, and stakeholders across growing-size supply chains. It requires the possibility to exchange data and information commonly interpretable by humans and machines across different enterprises. Given its relevance from a UM perspective, Enterprise Interoperability is investigated throughout a Systematic literature review in order to analyse the state-of-art and the related challenges. This work explores such a concept by looking at three different approaches (Federated-, Middleware-, and Model-driven-Interoperability) and five areas of application and research (Enterprise Modelling, Semantic & Ontologies, IoT, CPS, and trust & security). Nowadays, the quest for interoperability in the manufacturing domain is of great interest among the research community. Despite a lack of a universal shared and accepted solution for each of the various areas analysed, several proposals, potentially capable to establish interoperability in different contexts, are outlined and discussed. According to its conceiver, elements of Universal Manufacturing can be spotted in many corporations, and this work can be considered as further evidence.

Key-words: Universal Manufacturing, Industry 4.0, Interoperability, Literature Review, Enterprise Networking

Abstract in italiano

La collaborazione tra sistemi aziendali appartenenti a domini diversi è diventata sempre più pervasiva. Con la trasformazione dell'industria manifatturiera e dei servizi verso una prospettiva di globalizzazione, è emersa l'opportunità di riconsiderare la progettazione delle imprese a venire. Questa ricerca nasce dal concetto innovativo di Universal Manufacturing (UM). In seguito alla presentazione dei fattori abilitanti, le principali proprietà dell'UM, tra cui l'interoperabilità, sono descritte. L'interoperabilità nell'industria 4.0 prevede la collaborazione tra entità fisiche e virtuali, produttori e stakeholder attraverso catene di fornitura sempre più estese, contemplando la possibilità di scambiare dati e informazioni interpretabili da uomini e macchine in imprese distinte. Data l'importanza in relazione al concetto di UM, l'interoperabilità aziendale viene analizzata attraverso una revisione sistematica della letteratura, al fine di analizzarne lo stato dell'arte e le relative sfide. Questo studio esplora il concetto esaminando tre diversi approcci (Federated-, Middleware-, e Model-driven-Interoperability) e cinque aree di applicazione/ricerca (Enterprise Modelling, Semantic & Ontologies, IoT, CPS, e trust & security). Ad oggi, la ricerca per il raggiungimento dell'interoperabilità è di grande interesse nel settore manifatturiero. Nonostante la mancanza di una soluzione universale, accettata e condivisa in ciascuna delle aree esaminate, nel corso dell'analisi vengono delineate e, successivamente discusse, varie proposte potenzialmente in grado di implementare l'interoperabilità in diversi contesti. Secondo il suo ideatore, vari elementi dell'Universal Manufacturing possono essere individuati in molte aziende; questo lavoro può ritenersi un'ulteriore prova.

Parole chiave: Universal Manufacturing, Industria 4.0, Interoperabilità, Revisione della Letteratura, Rete Aziendale

Contents

1. Introduction

Traditional manufacturing has been centralized and guarded with regard to its operations and assets. This has been particularly relevant to businesses with market-dominating products. Once globalisation has led manufacturing to become distributed, enterprises explored production across international location, mostly driven by lower production costs [1]. Recently, the concept of Industry 4.0 has been accepted by numerous countries, businesses, as well as academic organizations following its characteristics of decentralization, connectivity and digitalization. Advancements in IC technologies such as Internet of Things (IoT), artificial intelligence (AI), and big data for industrial applications, have had an influence on the manufacturing sector growth [2].

Indeed, industry has continuously evolved around powerful technology developments over the last decades. The growth path has been rather steady, disruptions were relatively minor and successfully managed to accomplish the best outcome. Notwithstanding, the recent COVID-19 pandemic has raised up significant awareness of natural disasters, as well as other potential disruptions and their remarkable impact on the manufacturing industry. Nowadays, the industrial environment is getting more unstable and uncertain thus, managing the decision space of progress is challenging [3]. New theories, models, algorithms, and applications are constantly being created thanks to the development of AI technology. Besides, some conventional production models are becoming more open as a result of a new industrial global order [1].

The above-mentioned events as well as further technological and manufacturing developments next discussed can be considered the enablers of a major manufacturing transformation: Universal Manufacturing (UM) [3]. The idea of Universal Manufacturing has been recently proposed by A. Kusiak and the fundamental principle of this novel paradigm is to have manufacturing enterprises formally represented in the cloud [4] while distributed manufacturing facilities will be the basis of the future Enterprise.

Looking at the as-is situation of the manufacturing industry, UM requires a greater level of formal enterprise representation, standardization, and production control. In this regard, a basic tenant of Universal Manufacturing is Enterprise Interoperability (EI). EI has to be achieved through a unified modelling language, shared standards for products and processes as well as consistency in the sharing of data across machines and software.

The interoperability quest has been addressed by the literature, gaining interest among the research community, since the 70'. In this review, the concept of (Enterprise) Interoperability is analysed throughout a systematic literature review aiming at identifying its state-of-art, gaps, and advancements over the last two decades. Following an overview of the Universal Manufacturing paradigm and of the interoperability concept, research methodology and content analysis are presented in the subsequent sections.

1.1. Universal Manufacturing Background

Technological advancements over the past few decades have enabled substantial developments in the industry domain. For instance, flexible manufacturing has emerged thanks to automation technology and similarly, digital manufacturing following the developments in artificial intelligence.

In particular, recent years have contributed to six enablers of Universal Manufacturing [3], six paradigms here discussed from which the new concept stems. All these paradigms can be considered as embedded in initiatives such as Smart Manufacturing or Industry 4.0.

1.1.1. Digital Manufacturing

Digital Manufacturing can be defined as a set of tools employed for information management, assisting the decision-making process throughout the manufacturing life cycle [5]. The rise of data-driven computing applications, such as computer integrated systems, simulation, information-sharing models, has led to the development of digital manufacturing, involving collaboration tools which support the designing, redesigning, and analysing the factory, the product as well as the manufacturing process in an integrated way. Therefore, digital manufacturing is the application of computer systems to manufacturing services, supply chains, products, and processes aiming at obtaining better performance and efficient decision-making.

The application of digital technology leads to a cyclic process where the product is designed conceptually and then innovated or reinvented through computer-aided design software [6]. These designs and processes are virtually simulated in order to check the feasibility of manufacturing the product. The latter is regularly monitored during the process through the use of inspection techniques and tested by computer aided quality control methods. Besides, additional functions within a company can digitalized: supply chain management to improve detectability, visibility, and responsiveness as well as Marketing to improve profitability etc.

1.1.2. Open Manufacturing

Open manufacturing is a model of socioeconomic production in which physical objects are produced in an open, collaborative, and distributed manner and based on open design and open source principles. The open manufacturing model emerges from largely globally distributed production facilities, an open system architecture, as broadly established for telecommunication and computing systems [1].

Such distributed systems process data all around the globe while utilizing different tools and software. In this context, companies are less guarded about their physical assets and operational procedures as a result of manufacturing processes taking place at distinct locations.

1.1.3. Cloud Manufacturing

Cloud manufacturing is an innovative manufacturing paradigm developed from existing advanced manufacturing models and enterprise information technologies under the support of cloud computing, Internet of Things, virtualization, service-oriented, and advanced computing technologies [7]. Cloud manufacturing enables global and on-demand network access to a virtualized, configurable, and shared resource pool, supporting the manufacturing processes as well as supply chain management. Therefore, is embraced by open manufacturing. To enable comprehensive sharing and circulation of manufacturing resources and capabilities, it transforms manufacturing resources and manufacturing capabilities into manufacturing services that can be controlled and operated in an intelligent and unified manner.

1.1.4. Shared Manufacturing

The concept of shared manufacturing has its roots in shared economy and allows self-organized individuals to get involved in manufacturing activities through peer-to-peer collaborations. The paradigm extends the scope and depth of resources sharing, enabling society-based manufacturing integration [8]. Shared manufacturing has been pursued in the manufacturing context for about a decade. The model has been discussed in relation to resource sharing among multiple production systems driven by the reduction in the investment cost. In this regard, a transferability benefit index was defined to identify the most promising resources to be shared [9]. Shared manufacturing is influenced by the "servitization" trend, industry 4.0 as well as cloud manufacturing, but it embraces its own specific attributes.

In particular, if cloud manufacturing focuses on the convenient and efficient provision of manufacturing service, imitating the process of computing service in Cloud Computing [10], Shared manufacturing focuses to accessing services and resources in a timely P2P manner to broaden the sharing scope and depth and offer flexible cooperation.

1.1.5. Sustainable Manufacturing

Recent developments and interest towards the idea of sustainable manufacturing are largely inspired by environmental concerns [11]. Scarcity of resources, climate change, and rising energy costs etc. Have shifted the responsibility (and willingness) of manufacturers to process sustainable products, in a sustainable manner, focusing on materials, process and supply chain waste reduction along their entire life cycle. In addition to emphasizing environmentally friendly production, sustainable manufacturing also encompasses social responsibility in its broader horizon [12]. Furthermore, the paradigm demands simultaneous focus on each of the three-sustainability pillar (people, planet, and profit).

The bibliometric literature review by Bhatt, Ghuman, and Dhir [13] examined the key concerns of sustainable manufacturing. The analysis's key findings were a demand for the integration of several sustainability concepts, such as circular economy, life cycle engineering, and corporate sustainability assessment. Indeed, circular economy is the key concept within the sustainable manufacturing idea; the pursuit of sustainability necessitates a change from a linear (produce, use, and dispose) approach to a circular (closed-loop) strategy comprising inverse logistics procedures.

1.1.6. Resilient Manufacturing

Recent COVID pandemic as well as the Russo-Ukrainian conflict have revealed the vulnerability of modern manufacturing systems to face disruptive changes [14]. Furthermore, the industry sector has generally believed that any disruptions could be handled to have a bearable impact. Establishing resilience among the supply chain has been the typical industrial reaction as the frequency and size of the disruptions increased. In fact, building up redundancy and flexibility improve the resilience of an enterprise from a supply chain point of view. These two fundamental properties directly contribute to reduce the impact of a disruption by keeping resources in reserve and building up capabilities to respond quickly [15].

Kusiak A. in [3] formulates the industrial resilience challenge as follows: "Given the origin-magnitude-duration space of all plausible adversities, the industry should be prepared to fence-off any possible combination of adversities occurring at any time"

Table 1 and 2, respectively illustrate the attributes of the different manufacturing paradigms in comparison to UM as well as the main concerns and opportunities resulting from the above enablers described.

Table 1- Attributes of the different manufacturing paradigms [4]

	Digital	Open	Shared	Universal	*Definition*
Agile				✓	*Adapt to changes in type and quantity of the product being manufactured*
Flexible			✓	✓	*Quick response to changes in customer needs and markets under quality and cost considerations*
Reconfigurable		✓	✓	✓	*Interchangeable manufacturing resources*
Resource Sharing		✓	✓	✓	*Manufacturing resources used by more than one enterprise*
Data driven	✓	✓	✓	✓	*Data collected is made available for development of different applications*
Model-based	✓	✓	✓	✓	*Data used for the development of models and digital replicas*
AI-based	✓	✓	✓	✓	*Smart devices used e.g., robots and machine learning algorithms*
Cloud-based		✓	✓	✓	*Models of different nature posted in the universal manufacturing cloud*
Service-based		✓	✓	✓	*Systems in the form of x-as-a-service*
Globally-optimized				✓	*Large-scale optimisation in different criteria across different systems*

Table 2 - Six enablers of UM: Challenges and opportunities [3]

Manufacturing enabler	**Main challenge**	**Main opportunity**
Digital M.	Generation of necessary data	Sharing of value from data
Open M.	Adoption of widely agreed-upon modeling methodology and standards	Presence in the cyber space and connectivity
Cloud M.	Conversion to the system-as-a-service operating model	Generate benefits of the system-as-a-service concept
Shared M.	Identification of available resources	Better resource utilization
Sustainable M.	Legislative and business concerns	Address environmental issues
Resilient M.	Development of comprehensive resilience model	Increase ability to withstand disruptions

1.2. Universal Manufacturing Overview

The innovative concept of Universal Manufacturing (UM) described by Kusiak A. is clearly at the beginning of its life. Nonetheless, thanks to the embracement of its enablers, UM is emerging at different levels, manufacturing equipment and technology, operations, and software [3].

According to the authors, one of the most remarkable benefits enabled by UM would come from sharing manufacturing models [16]. Admitting that properties and requirements are likely to emerge in the course of future developments; currently, the main characteristics outlined are:

- **Many-to-many relationship**. In Universal Manufacturing, the relationship between product and system follows a many-to-many model as shown in figure 1. In such a way, various products can be produced by different facilities. The graph is advisable to be densely connected under an efficiency perspective.

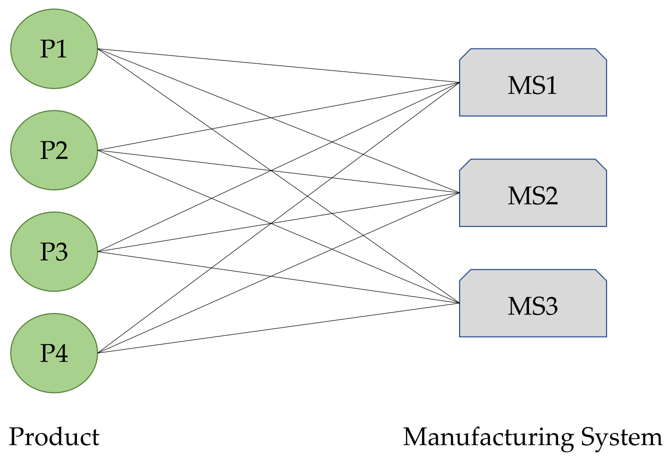

Figure 1 - Many-to-many product-manufacturing relationship

Nowadays, positive peaks in production demand are managed through capacity expansion. Although, the convenience of the capacity expansion model is experienced only for long-term system growth. On the contrary, assembling a model that involves processes distributed over different locations would allow to successfully handle sudden spikes in demand.

- **Formalization of enterprise model**. UM elevates open manufacturing to a higher level of formal representation and standardization throughout the whole enterprise. Enterprise models, in particular, are defined as optimized subsets of the UM model created to satisfy specific production requirements. These models might become the most important differentiators of enterprise business strategies since they would be optimized for the particular organizations [3].

- **Enterprise interoperability**. Clearly, interoperability of data as well as of manufacturing models is essential to Universal Manufacturing's success. Interoperability is needed to facilitate efficient information exchange, coordination and communication across various facilities and organizations. Farther, Enterprise interoperability can be considered as an additional step with respect to the formalization of enterprise model. It does not only refer to internal standardization but has a broader scope towards efficient external coordination.

- **Adaptability.** The definition of adaptability in relation to UM comprises properties such as flexibility, reconfigurability, and agile manufacturing. Indeed, UM systems would handle different parts, in different quantities through different potential process routings. Such systems would be designed for handling rapid changes of their structure according to the market needs. Moreover, both internal and external uncertainty are meant to be strategically managed in the view of agile manufacturing.

- **Affinity.** Affinity (e.g., similarities) among processes, services as well as, resources and products would be exploited by Companies. These factories are supposed to work with equipment that are part of a superset, distributed across many enterprises, and produced by a limited number of original equipment manufacturers. This solution would offer better alternatives in terms of additional capacity, larger volume, personalization, also in compliance with sustainability and resilience.

Among the above-described properties, Enterprise interoperability is further analysed in the following sections. Indeed, given its relevance from a UM perspective, interoperability can be considered as a fundamental requirement to achieve an efficient and effective coordination among the distributed facilities of the future enterprise conceived by Kusiak A. Following a brief background of the concept, interoperability is investigated through the literature to depict its state-of-art and challenges, overall contributing to a successful implementation of the Universal Manufacturing model so far described.

1.3. Interoperability Background

Enterprise networking is nowadays a reality for great part of businesses, including institutions, service providers, and industrial corporations. Supply chains have grown as a result of market globalization, leading even small companies to be part of a much bigger network. As a result, there is now a requirement to coordinate with other organization members, preserve solid partnerships, interact, and coordinate with other commercial organizations, whether they are based nearby or elsewhere on the globe.

It can be assumed that Internet computing as well as ICT technologies have enabled such cooperation on a technical level. Notwithstanding, Enterprise integration and interoperability, which are involved whenever different corporate organizations need to collaborate, share data, or information, also take organizational and semantic aspects into account.

In order to clarify the two different terms, if enterprise integration relates more on an organizational dimension, interoperability has more a technical nature [17]. According to D. Chen, et al [18], interoperability denotes "coexistence, autonomy and a federated environment" whereas integration refers to "coordination, coherence and uniformization".

Thus, Enterprise Integration considers the coordination of business, processes, people and technology of the enterprise in a strong standardized and uniform ways. Such integration can be distinguished in three types:

- **Full integrated** or **interfaced systems**: single components are not more distinguishable. The systems can only exchange data through predefined protocols and schema.
- **Tightly coupled systems**: components are distinguishable but any modification on them will be perceived by others. All data sources are integrated through the creation of a logical mapping using standardized hard-coded interfaces, predefined global schemata and requiring the so-called integrating infrastructures [19].
- **Loosely coupled systems**: data components are coordinated autonomously and can work as part of the integrated system too.

The latter case corresponds to interoperable enterprise systems next discussed. Indeed, enterprise interoperability equates to loosely-coupled enterprise integration [20]. The Webster dictionary define interoperability as "the ability of a system to use the parts of another system".

To first discuss technical, semantic and organizational aspects of enterprise interoperability, the European Interoperability Framework (EIF) is used as a baseline. The concept of interoperability has been defined by the EIF corporation as:

"The ability of organisations to interact towards mutually beneficial goals, involving the sharing of information and knowledge between these organisations, through the business processes they support, by means of the exchange of data between their ICT systems" [21].

The following European Interoperability Framework (figure 2) has been developed by the European Union and the European Commission. It defines the three fundamental levels of interoperability.

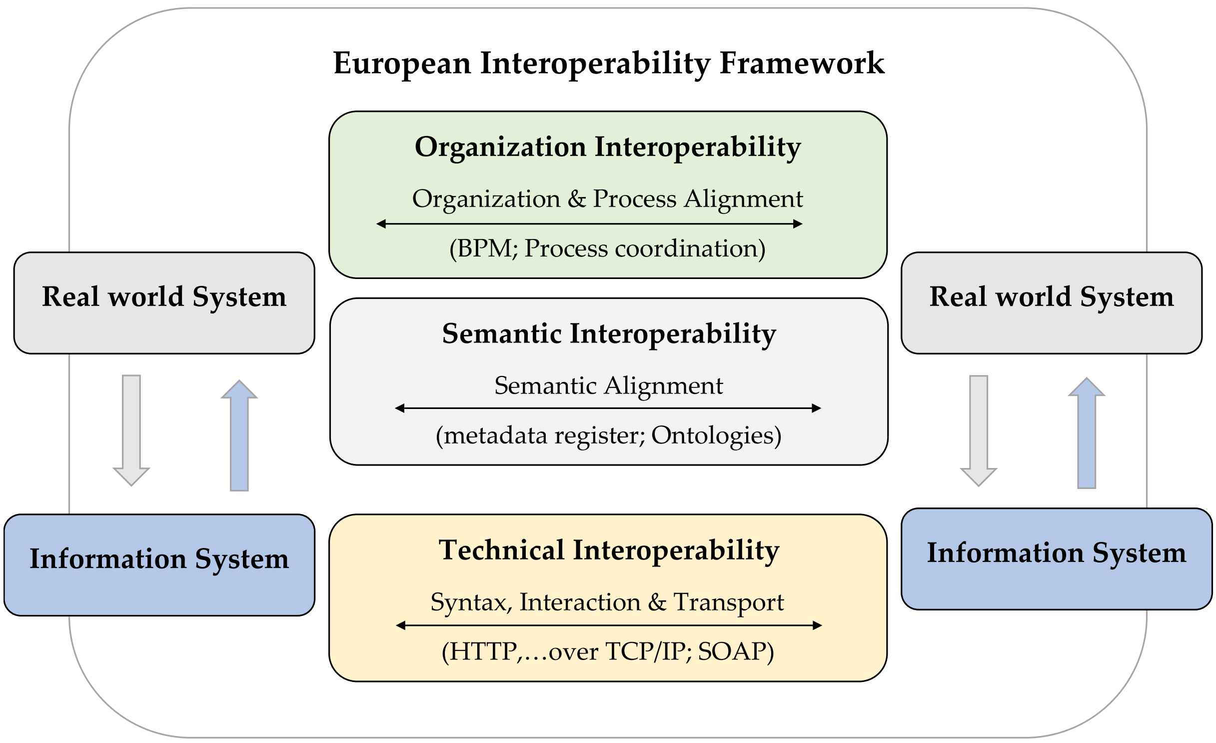

Figure 2 - European Interoperability Framework, retrieved from [17]

- **Technical layer**: represents the technical aspects of enterprise systems interoperability which provide the technical foundations. It is also called the syntactical aspects of interoperability. For instance, it deals with supporting communication, data exchange and interchange in terms of communication protocols.

- **Semantic layer**: the semantic aspects of interoperability refer to knowledge and information sharing through data integration and consistency to support cooperation. Semantic interoperability is the ability to share, aggregate or synchronize data across heterogeneous information systems [17]. Thus, it has to deal with consistent communication across different systems, enabling seamless interpretation of shared data/information.

- **Organizational layer**: organizational aspects of interoperability refer to the definition of business goals, aligning and coordinating processes and bringing collaboration capabilities to organizations that want to exchange information and may have different internal structures and processes [17]. Therefore, organizational interoperability is the companies' ability to provide services to each other and to customers.

Each of these dimensions defined by the EIF is characterized by several challenges and gaps to be filled up. For instance, the need of compatible systems despite the high heterogeneity identifiable on the market, a common language to express data, models, and processes as well as the presence of different human and organizational behaviours, structures, or management approaches. Furthermore, additional challenges in building interoperable systems have been highlighted by Vernadat F. in [17]: Trust management, security issues, confidential issues, legal issues, and linguistic issues.

1.4. Interoperability in Universal Manufacturing

A Universal manufacturing Enterprise will be established based on the distributed manufacturing facilities [3]. Interoperability among them would enable efficient and effective demand handling and capacity management. Also, significant impacts would be perceived along the supply chain network. Indeed, increased transparency, data and information exchange, allow supply chains to have greater accuracy (e.g., in inventory management, production planning, operation waste etc.), enabling prospective automation [22], and improve supply chain response against potential disruptions.

In particular, interoperability as well as connectivity of manufacturing models for data and information sharing are key to the success of UM. According to Kusiak A., standards represent a solution to facilitate systems interoperability. Besides, other type of solutions (e.g., models, framework etc.) should encompass many different aspects within an enterprise: modelling languages, modelling for components and products, system modelling, architecture approaches including also organizational and security aspects.

In this light, a systematic study of literature concerning methodologies, standards and other type of solutions for achieving interoperability is proposed, aiming at answering two questions:

1. *What is the state-of-art of industrial interoperability with a view to universal manufacturing?*
2. *Which challenges about interoperability are recognized by the literature?*

2. Research Methodology

The research method utilized in this work is a systematic literature review (SLR) [23], to collect an extensive view of the interoperability concept concerning the manufacturing domain. The SLR has been developed following a multi-step approach:

1. Definition of a framework
2. Definition of the research protocol
3. Systematic review implementation
4. Research content analysis

2.1. Definition of a framework.

Having an overview of the dimensions and the state-of-art about interoperability in the industry sector hints at the development of a framework through which the literature can be analysed. The creation of the framework was an iterative process. Indeed, it has been delineated along with the development of the content analysis, given the difficulty related to a preliminary and complete definition of the different interoperability extents that would have been subsequently encountered.

This research deals with Enterprise Interoperability[1], following the Universal Manufacturing paradigm. Accordingly, the Enterprise Interoperability concept has an implicit variety as, in an intra- and inter-enterprise context, there is a vast range of tools, software, machines, data and processes, and interoperability can be potentially achieved for all of them. Therefore, the framework has been developed assuming an appropriate perspective: neither it focuses on the single interoperability layers defined by the EIF (namely technical, semantic and organizational), nor it exclusively looks at other definitions that have been developed over time. Indeed, Ford et al. [24] in 2007, identified 64 different interoperability types. Thus, as shown in table 3, interoperability has been researched by analysing:

[1] Enterprise interoperability is concerned with interoperability between organizational units or business processes, either within a large distributed enterprise or within a network of enterprises [111]

- Frameworks/models resulted as the most researched and adopted to achieve interoperability (Federated, Middleware and Model-driven).
- The most relevant areas of interests in which interoperability is researched (Enterprise Modelling, Semantic & Ontologies, IoT, CPS, Security & Trust) Identified during the iterative process, they are associated to an Enterprise and its operation.

By grouping different interoperability-related works coming from disparate manufacturing domains, a part of the documents falls in more than one 'category' suggested by the framework.

Table 3 - Framework used to map the literature review

Interoperability	Description	*Ref.*
Federated	An approach according to which no common format but dynamic accommodation is established within and between enterprises.	[25]
Middleware	A layer between software applications (e.g., enterprise applications) and system resources, which abstracts the functionality of operating systems or interfaces to provide interoperability	[26]
Model-Driven	A methodological framework, based on the Model-Driven Architecture approach, which provides conceptual and technical support to make interoperable enterprises through the use of ontologies and semantic annotations	[27]
Enterprise Modelling	the abstract representation of a business's structure, operations, procedures, data, resources, relationships (with all stakeholders), and all activities necessary to generate industrial goods or services. Interoperability under this perspective addresses the challenge of a unified enterprise modelling language	[28] [29]
Semantic & Ontologies	Semantic interoperability is defined as a common semantic interpretation of knowledge and is achievable when the knowledge and information acquired can be efficiently communicated in a collaborative setting without any meaning or intent being lost in the process. Ontologies are semantic models that can formalize a great level of details supporting reasoning, enabling the acquisition, exchange and processing of information and knowledge based on their semantics	[30] [31]
IoT	IoT refers to the networking of physical and virtual entities over the internet. In this domain, interoperability refers to the ability of various IoT deployment components to efficiently interact, share data, and work together to achieve a common goal.	[32]
CPS	Cyber-Physical System (CPS) refers to a generation of digital systems which mainly focus on complex interdependencies across the cyberspace and physical world. Several powerful software tools are exploited but it is still difficult to combine these into tool chains for better efficiency.	[33] [34]
Trust & Security	Trust is a function of the partner's reliability, behaviour and commitment. The notion is analysed together with security issues that may arise during collaborations among enterprises. Indeed, enterprise networking requires businesses to openly share services across Internet infrastructures, expose information systems, and exchange a lot of knowledge and information	[17] [20]

2.2. Research protocol

The protocol gives details of the plan for the review. In particular the selection of primary studies has been restricted to:

a. Only English written documents with full text available.
b. Peer reviewed journals, conference papers, and book chapters.

After the definition of suitable eligibility criteria, adequate keywords and Boolean operators were selected to cover the interoperability concept in the literature. As presented in table 4. The research has been divided into two steps, related to different research queries:

1. A first query was used to acquire a vast baseline of interoperability-related documents. Thanks to this, the concept has been explored in its different forms. It contributed to the draft of the framework as well.
2. Subsequently, a second query, smaller in terms of resulting articles, has been used to deepen the concept and refine the main body of literature analysis.

Table 4 - Keywords for the literature review

	Interoperability-related	**Business-related**	**1st Keyword**	***Query***
↑ *OR* ↓	Internal External	Manufacturing	Interoperability	1st
↑ *AND* ↓	Enterprise Model*			2nd
	←*AND* →		←*AND* →	

The three main parts of documents (title, abstract, keywords) were used to implement the search technique. Besides, for the first query, in accordance with its scope, the research of keywords and Boolean operators has been extended to the full text of documents. Eventually, the addressed database was Scopus, relevant for the industrial engineering sector.

2.3. SLR implementation

The literature search is conducted using a methodology that is similar to that used by the majority of SLRs (*e.g.*, [35]): duplicates removal, application of eligibility criteria, title and abstract screening, full-text reading, and snowball analysis. This process is summarized in figure 3, starting from 1’411 documents (1st query) and 299 documents (2nd query) to finally coming up with 65 plus 39 eligible documents relevant to the research questions. Journal Papers represent the majority followed by conference papers which account for the 30% of total documents (figure 5).

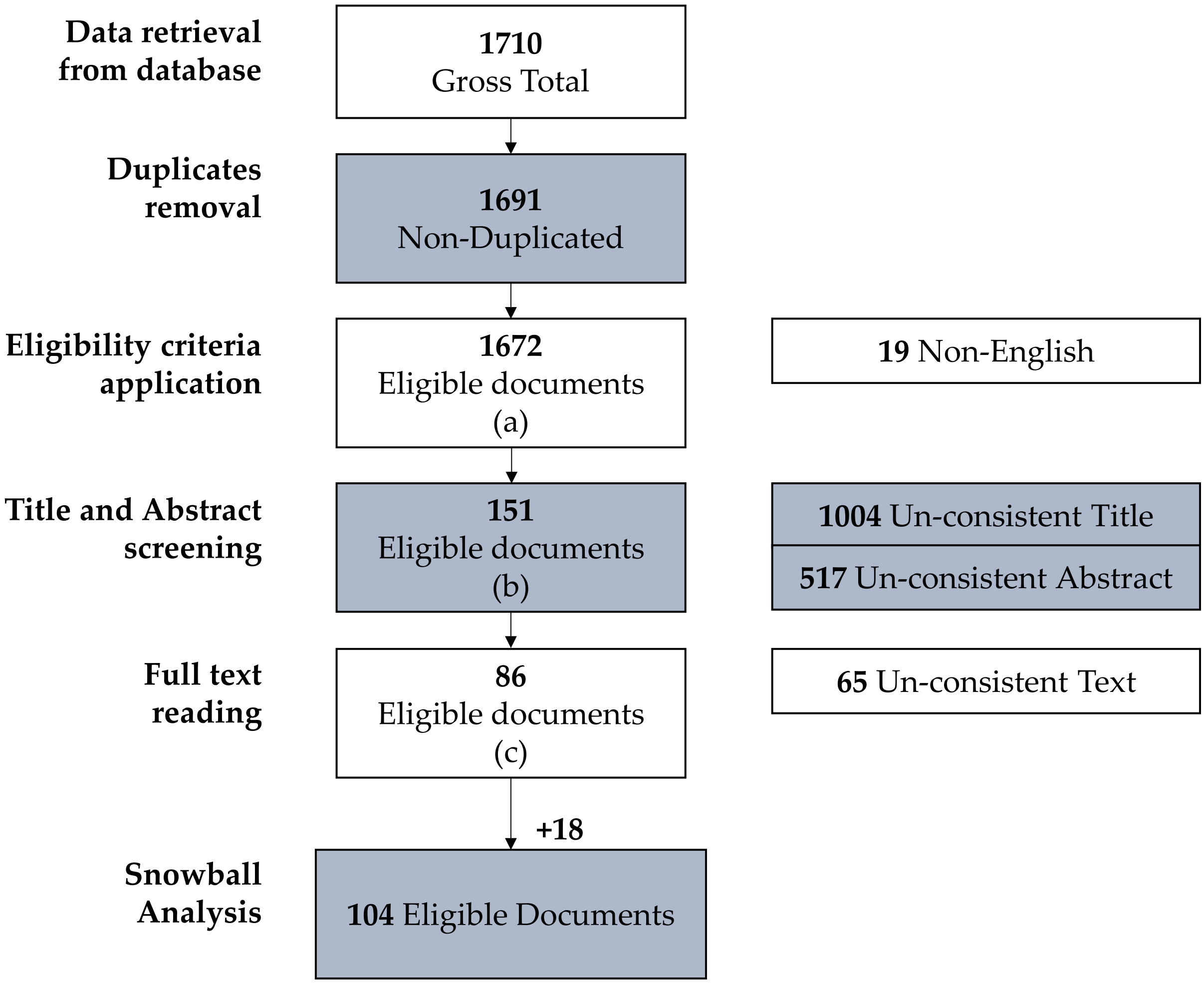

Figure 3 – Literature Search Process

3. Descriptive Analysis of eligible documents

Although the interoperability research field comes from a different group, the discourse on tool integration shares many discussion topics with it [34]. Similar to the tool integration research field, interoperability has garnered an increasing interest in the research community since the 1970s. Resulting in a remarkable growing share of research literature related to interoperability, as shown in figure 4.

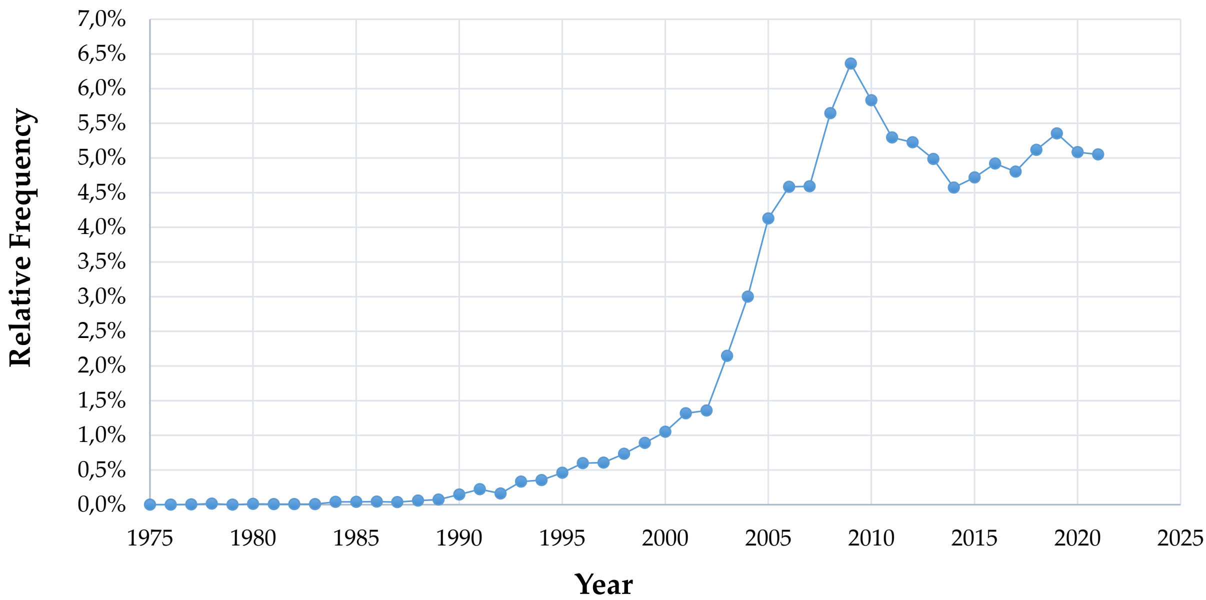

Figure 4 - The relative frequency, in percentage over time, corresponding to the "interoperability" keyword. Generated by Scopus results.

As a result of the SLR implementation, 104 eligible documents from 2001 to date (figure 6) allow delineating the state-of-art of literature research, signs of progress as well as current challenges about interoperability in the manufacturing domain. Document statistics and related subjects are descried in this section.

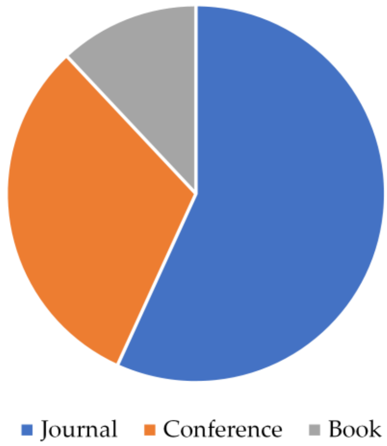

Figure 5 – Eligible documents types statistics

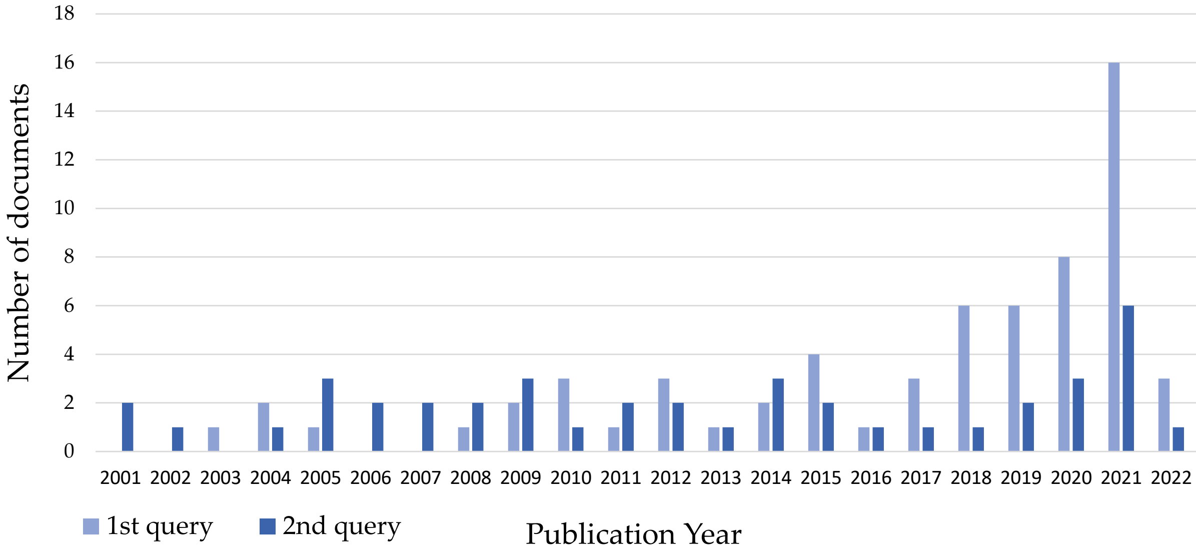

Figure 6 - Eligible documents biographical statistics

3.1. Addressed topics statistics

Along the literature search process, a major reason for exclusion referred to the subject covered by the papers. For instance, astronomy, medicine, psychology, and further topics were considered as not relevant for the study. Additional exclusion grounds related to:

- Papers unconnected to the manufacturing domain. The sector was detected by looking at the title and checked in the abstract screening
- Papers only focused on small-scale experiments
- Papers with a purely technical focus and/or very specific, with insufficient coverage of the interoperability matter
- Not accessible papers

As shown in figure 7, half of the papers come from the Computer Science and Engineering discussion. Additional relevant domains relate to Business, management and accounting, Decision science, and Environmental science. These five subjects covered more than 75% of the 1710 starting documents. Such a prevalence is even more observable after the eligibility criteria application and text screening, overtaking 90%.

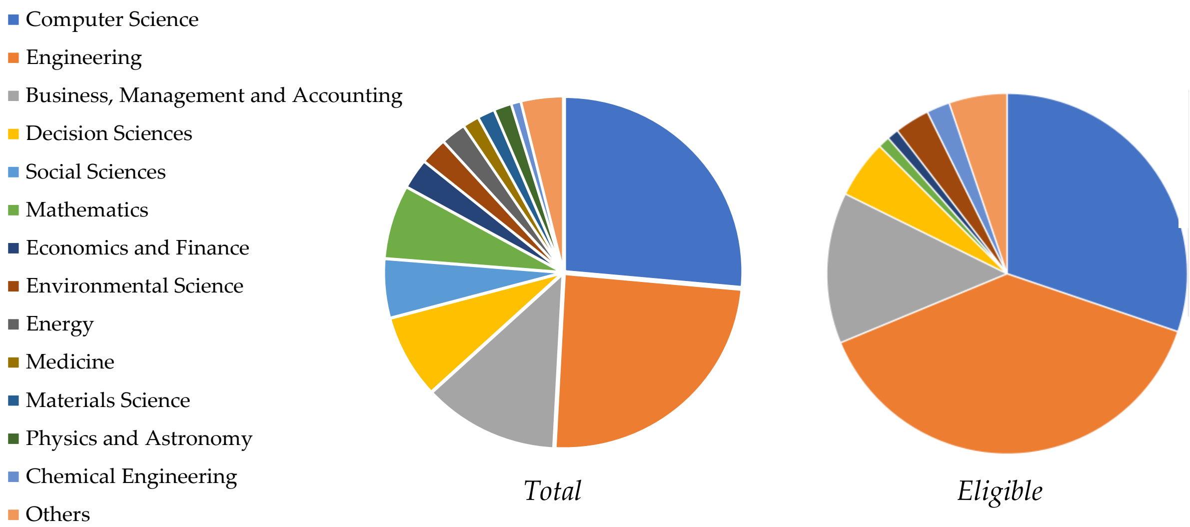

Figure 7 - Documents subjects pre- and post- SLR implementation

The 104 documents were mapped with reference to the framework presented in the previous section. Figure 8 shows the queries' contributions in each interoperability-related category. As anticipated, various papers fall into more than one division thus, the total sum overcome 104.

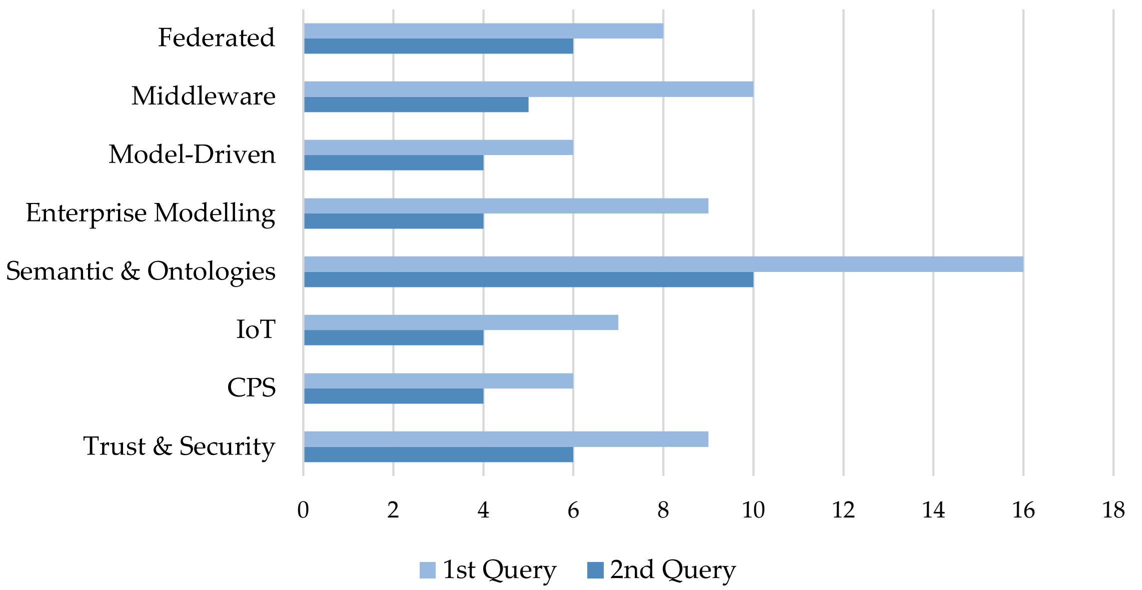

Figure 8– Eligible documents' classification

4. Research content analysis

The authors of the eligible documents describe and analyse interoperability under different perspectives, underlining gaps and areas of improvements. The analysis shows that current interest is diversified according to the level, context and application within which interoperability is intended to be accomplished.

In line with the goal of obtaining an extensive perspective about interoperability, especially with regard to the first query used during the SLR, a date (year) after which applying the eligibility criterion was not defined. Therefore, the selected articles range from 2001 up to date. Due to this temporal gap, the context in which interoperability has been studied has evolved. In earlier articles, some topics are only briefly touched upon or presented; in more recent ones, these concepts are taken and deepened.

Therefore, the following content analysis conducts a chronological investigation. In most sections, authors' works, results and proposals are reported starting from the oldest in terms of the publication date. Accordingly, signs of progress and developments that filled eventual gaps as well as challenges that arose are highlighted.

4.1. The Heterogeneity challenge

Despite the selected documents span a variety of contexts and publication years, a common element in the vast majority of papers is related to the concept of heterogeneity. In particular, enterprises must limit 'heterogeneity' in order to reach interoperability [36].

Indeed, the next generation of industrial systems was anticipated to be highly interoperable throughout devices and components coming from different domains. As a result, the quest for interoperability across systems and processes is rapidly gaining more and more interests [37]. However, this integration is significantly complicated due to the extant diversity and heterogeneity of technologies and standards. Although focusing only on an organizational level, Rauffet et al. distinguish three types of heterogeneity (Table 5). Clearly, heterogeneity levels are linked to the ones defined by the EIF and can be seen as the main obstacles to reach interoperability. Blanc et al. [38] advocate also materials heterogeneity as a synonym for the technical one concerning information technology, hardware and software.

Table 5 - Three levels of heterogeneity [36]

Heterogeneity	
Semantic	Related to syntax and language problems (signification of speech, sense of the knowledge which can be proceeded and manipulated in the enterprise). Coming from the fact that systems are built and used by different people, in different places at different times, with different aims and vocabularies.
Organizational (or funcitonal)	Caused by differences in the practices and business processes. Indeed, different enterprises and departments may grow and develop their own organization isolated from another. Consequently, same tasks may not be processed in the same way in two different organizational units and problems can occur at their cooperation border.
Technical	Resulting from the use of several materials to transport, transmit, and operate information which are not compatible.

As anticipated, several authors raise the problem of heterogeneity in an effort to achieve complete interoperability in their respective fields and disciplines. Some examples are reported below.

Grilo A. et al. [39] emphasize the presence of many heterogeneous applications and systems typically in use by the different stakeholders, thwarting the dynamics and adaptability needed to interoperate in the AEC sector. Heterogeneity of data sources (e.g., databases, sensors, devices etc.) is well addressed by Pang L.Y. et al. [40] in the context of ubiquitous enterprises, strongly limiting information integration and impacting on the efficiency and effectiveness of decisions.

Thus, heterogenous information coming from different domains represents a consistent obstacle. As a consequence, requirements misinterpretation and mistakes have been identified during the product design and manufacturing phases [41].

In [42], Margaria T. et al. recognize Industry 4.0 as inherently heterogeneous for the way it has grown and, in general, in the Cyber physical Systems (CPS) realm. In addition, farther authors as Panetto et al. [43] observe how ontology modelling methodologies are varied and, even if several best practices exist, the practice of reusing extant knowledge is not completely exploited, resulting in an uncoordinated and heterogeneous ensemble of ontological models and ontologies. The latter concern is also related to semantic: A. Gal et al. [44] define the multiple representations of an artefact or concept as "semantic heterogeneity", which is an obstacle to the manufacturing process.

Therefore, heterogeneity can be seen as a major challenge to be solved in order to solve the interoperability quest, which is at the heart of every system and system-of-systems project [42].

To accomplish interoperability in its many declinations, the authors of the eligible documents propose solutions, frameworks and models. In this chapter, the SLR results are organised according to some of the most relevant approaches used to address the problem (*section 4.2 - 4.4*) as well as areas and context within which it is researched (*section 4.5. – 4.9*).

4.2. Federated Interoperability

In one of the oldest publications analysed, Chen et al. [25] attempt to establish a foundation for future advancements concerning the interoperability of enterprise applications. The relevance of semantics and the fact that meaningful interoperation is meant to be achieved at all levels of enterprise, not only the data, is emphasized. Besides concepts and definitions, three scenarios to develop interoperability are advocated (table 6). They can be considered as three ways, three approaches to relate two or more entities. In particular, federated is recognized as the most promising one in the context of enterprise interoperability. Such a view is shared by several other authors in the late literature.

The main reasoning is linked to feasibility: most models will not be in a standardized or common form because it is not economically feasible. The cause of the problem can be attributed to the heterogeneity of enterprise applications. Accordingly, in a federated environment, no parties can impose their format, language, or models but dynamic accommodation and adaptation shall be implemented. New standards and even new models could this way be made compliant with existing state-of-the-art ones.

Table 6 - Three interoperability scenarios [25]

Paradigm	Description	Approach
Integrated	Standard format for all models, The format must be as detail as models	Standardization, Mapping to the standard
Unified	Common format only exists at a meta-level, Meta-model is not an executable entity	Must have a pre-defined meta-model for semantic equivalence, Mapping via meta-model
Federated	No common format, Dynamic accommodation	Must share an ontology, Concept mapping done at ontology level

In [45] Figay propose a Federated Interoperability Framework (FIF) aspiring to reach enterprise applications as well as sustainable product and process data interoperability. The framework is based on the use of open standards for Manufacturing Domain, Information Systems (IS) and ICT. Accordingly, Moones et al [46] take the FIF as a basis for introducing a methodology for dealing with Dynamic Manufacturing Network and addressing the lack of an adjusted methodology for use cases and test scenarios, which are an interoperability bottleneck. Ten years after its introduction, Tchoffa et al. [47] report the FIF development by the Airbus Group Innovation and support its use to address new interoperability challenges brought on by the use of disruptive technologies like IoT, blockchain, Big Data, or Cloud.

Additional recognitions relating to a favorable utilization of the federated approach is presented in [48] in which the authors introduce a baseline to develop an Enterprise Operating System (EOS) by setting loose coupled connections among enterprise's software under the perspective of federated interoperability. Therefore, to provide rapid interoperability establishment and dynamic environment updating, the collaborating parties must make accommodations and modifications "on-the-fly". Indeed, Panetto et al. assert that a federated approach shall enable the so called "on the fly" interoperability relationship [49].

In [50], the authors consider the next generation of Enterprise Information System (EIS), describing them as inherently interoperable and operating in a federated context. In particular, a federated environment is advocated as a promising solution to address semantic heterogeneity (*section 4.6*). A more practical approach is presented in [51] by Labreche et al. Indeed, the authors propose a methodology for implementing federated interoperability through an automated model transformation, supported by evaluation to ensure data retention and consistency. Such a global approach is based on graph theory, transforming elements of a model into a set of nodes and the various links between the elements into edges. The model enables to translate data 'on the fly', ensuring a smooth and collaborative workflow in the context of collaborative networks. Nonetheless, the authors recognize conceptual, technological, and organizational barriers while implementation is said to be a future step of the research.

Besides, Zacharewicz et al. in 2020 address the interoperability problem in the Supply Chain of ICT discussing different models and model-driven approaches. Still, the federated approach is described to be little developed but to be one of the research challenges of the next years as it is appropriate for an interorganizational setting and seeks to achieve full interoperability [28]. Indeed, the federative approach has been put in practice in recent years.

Further examples are reported in [52], in which Gorecki et al. propose a modelling and simulation method and a DMSF platform. The latter is a federative platform capable to bring interoperability to several modelling and simulation languages and components. Moreover, a High-level Architecture (HLA) is used to enable communication and data exchange between different simulation tools: Papyrus and Jaamsim. The work has been later extended in [53] where, still thanks to the use of a HLA, the possibility to extend Papyrus, untying it to other methods and technologies is demonstrated. Thus, adding modelling and simulation components without impacting the basic model.

4.3. Middleware for Interoperability

To deal with heterogeneity within large and dynamic enterprises, different solutions are based on the use of some standards, focusing on the interconnection of a limited number of software, devices… but also middleware solution, in order to overcome the problem [49].

In this review, middleware follows the definition as a layer between software applications (e.g., enterprise applications) and system resources, which abstracts the functionality of, for example, interfaces and operating systems to provide interoperability [26]. To support an intelligent network between assets, the software architecture of middleware must be able to reconfigure the communication among the services within and so, accommodate changing requirements [54]. Indeed, several middleware solutions have been encountered throughout the Systematic Literature Review implementation.

In [55] Penciuc D. et al. discuss the most used approaches to support interoperability namely, Semantic web Technologies, Standards and Web Services. The latter consists in utilizing a dynamic interface based on application programming and web technologies to support the distribution of heterogeneous information. It is the basis of authors proposals, in which an independent PLM connector allows synchronization of the objects used across heterogeneous systems. In particular, a flexible architecture was designed to provide a generic connector. However, the authors recognize the necessity of testing the prototype in new industrial scenarios and to investigate further requirements. In the context of ubiquitous enterprises, Pang L.Y. et al. [40] raise the importance of information systems for supporting collaborative decision-making process. Notwithstanding, as discussed for the heterogeneity challenge, their important role led to the adoption of different systems increasing the difficulties in data interoperability. Therefore, the authors present an innovative data-source interoperability service (DSIS), a middleware to connect and enabling interoperability between heterogeneous data sources. The platform is described and presented in terms of design and implementation. It offers a uniform platform to integrate web services and software agents, facilitating application and device cooperation inside an enterprise [40].

Middleware is also used in the context of Cyber physical systems. Indeed, Givenchi O. et al. [37] propose a middle layer which maps descriptions and data coming from physical devices and components into a common information model acting as an intermediate between physical and cyber layer enabling interoperability. In a wider context, Benaben et al. [56] highlight need to create farer, faster and more computerized collaborations. In this regard, they present a Mediation information system engineering approach to improve interoperability for enterprises' collaborations. Indeed, the objective is a mediator system able to manage data and information exchange without constraints. The approach uses mapping rules to transform model from the business to the technical one and would cover the whole path from the early stages of design to runtime and implementation.

Within the scope of internal supply chain, the authors of [57] propose a framework for intelligent automation to deal with the challenges in acquisition and management of data, towards the improvement of decision support systems. In particular, the flexibility and interoperability of data required by the different layers (from shop-floor to business planning) are addressed through a middleware, which connects all layers simultaneously and in real-time with decision support systems. Moreover, Coito T. et al discuss middleware approach in comparison to others, recognizing that it has the advantage of avoiding full peer-to-peer communications, by creating single access points between decision support systems, automation, and remaining systems. A major implication related to the development of such a framework is that it can help practitioners addressing the most impactful challenges (as interoperability and real-time data exchange) affecting internal supply chains performances.

Recently, in [58], Pakala et al. discuss some of past proposals and works in the context of middleware architectures for enabling message exchanges in a multi-protocol environment. The result of such an analysis shows that seamless interoperability is still far to be reach: some proposals need higher level of consistency and configuration overhead, some others seem to be better options but durability is uncertain and the middleware may end up in bottleneck. Next, the authors assert the possibility of a better solution in terms of middleware architecture enabling seamless exchange of messages thus, by addressing the issue of interoperability: the Registry Infrastructure Component (RIC). RIC is a middleware gateway acting as a bridge for the exchange of messages, in an Industry 4.0 context, between different communicating Asset Administration Cells [58]. Performance evaluation is declared to be a future scope.

A further recent improvement concerning middleware to address interoperability is presented in [59], in which Kiesel R. et al. describe the Middleware+: a central platform for communication, essential in the IoP (internet of production) and facilitating the exchange between agents. Although it is not a novelty, previous works didn't define precise requirements to ensure its effective implementation. Therefore, the authors research the functional requirements of Middleware+, here summarized in table 7. They were taken from published academic studies and each addresses a different aspect of what a Middleware+ needs to be able to handle [59].

Table 7 - Functional requirements of Middleware+ [59]

FR	Description
1	M+ ingests data from all field devices in all relevant formats and uses function calls for bidirectional communication flows. (Rojas and Ruiz Garcia, 2020)
2	M+ mediates between data sources and consumers. All devices are uniquely identifiable under a data governance regime that implements user management as well. (Otto et al., 2016)
3	M+ converts data and methods to an inherently semantic, searchable data format and offers it via a single interface. (Song et al., 2009)
4	If no data model is specified, the user builds it from standard components and saved for administration. All data and information models are stored. (Kefalakis et al., 2019)
5	M+ offers tools for data processing and synthetic variables. (Liebenberg and Jarke, 2020)
6	M+ executes CRUD queries on all available databases of the organisation with respect to the database type. (Curry, 2020, p. 57)
7	M+ differentiates data flows according to their importance and urgency to provide optimal reliability and availability. (Anderl et al., 2020)

The presented approach is said to be potentially capable of laying out a path for semantic and non-semantic data to cooperate in an industrial architecture.

4.4. Model Driven Interoperability

As anticipated, the interoperability quest is addressed by the literature through the use of different methodologies. In this review, besides the description of Federated and Middleware techniques, a remark concerns Model driven interoperability.

Nowadays, the model driven approach is followed by several projects and communities like INTEROP (2007) in the European Union and model-driven architecture (MDA) carried out by the Object Management Group (OMG). In particular, MDA is a software design approach for the development of software systems which aims to encourage the use of models as the primary method for creating and implementing various types of systems [60]. It provides a set of guidelines for the structuring of specifications, which are expressed as models [27]. Such kind of approach is often used in the enterprise modelling context (*section 4.5*). Accordingly, Model Driven Interoperability (MDI) can be defined as a methodological framework, developed by the task group TG2 of the Interop-NoE European project (2007), relying on the MDA approach, which provides conceptual and technical support to make interoperable enterprises through the use of ontologies and semantic annotations.

Huang H. et al., analysing the characteristic of manufacturing process in various manufacture enterprises, take advantage of the Model Driven Architecture methodology in order to construct a dynamic reconfiguration manufacturing execution system. Which, according to the authors, can solve the problems of portability, information integration, and interoperability effectively [61].

It's relevant to notice that the use of such approaches does not neglect the other techniques previously discussed. MDI can be seen as a process to support the development of interoperability in its disparate declinations. For instance, in the work presented by Benaben et al. [56] the objective is a mediator system, as discussed in the previous section (*4.3*), but it consists of a model driven approach used to construct Information System for new collaborative enterprises. Furthermore, the reported work by Labreche M. et al. which presents a methodology to deploy on-the-fly federated interoperability has a twofold objective. Indeed, the authors want to show that the combined adoption of concepts from graph theory and Model-driven engineering allows facilitating the establishment of on-the-fly federated interoperability as well as making the implementation of evaluation mechanisms easier and more uniform among heterogeneous systems [51].

Additional application examples are present in [62], in which Aghostino et al. discuss about MDSEA (Model-Driven Service Engineer Architecture) to unify every step of the enterprise servitization: from specifying application's business requirements, to deployable services. Looking at characteristics as portability and interoperability, the framework is based on MDA/MDI. Also, Figay N. et al. [63] propose an innovative model driven approach which combines enterprise modelling, business modelling, information system modelling and ICT modelling aiming to achieving interoperability in Dynamic Manufacturing Network. Eventually, in [28] the authors elaborate the MDISE (Model Driven Interoperability System Engineering) that addresses the vertical and horizontal interoperability model driven approach between enterprises extending the existing MDSEA (model Driven system engineer architecture) which focuses on integration among internal domains before connecting the different models.

Having presented an overview of three relevant techniques (federated, middleware, model driven) found in the interoperability-related literature, the next sections (*4.5-4.9*) intend to delineate remarkable areas of applications. Within each section, following clarifying definitions, authors proposals are presented in a chronological way.

4.5. Enterprise Modelling

This section presents a series of definitions and proposals to address interoperability in Enterprise modelling (EM). Kusiak describe an Enterprise model as *"an optimized subset of the universal manufacturing model formed to meet the specific production needs. The optimization criteria and constraints of the enterprise formation model will be enterprise specific and may become the strongest differentiators of enterprise business strategies"* [3]. Indeed, one of the conditions advocated by the author to implement the concept of Universal Manufacturing is a widely accepted standard modelling methodology.

EM must be able to represent several points of view related to the modeler's needs (e.g., structural, functional or behavioural) expressing the reality at different levels (conceptual, organizational, and technical). Usually, a specific approach is linked to each modelling language, characterizing the steps for building and using the model. This explains why the research works in the domain of enterprise modelling have led to many languages and modelling tools [29]. Therefore, Interoperability under this perspective addresses the challenge of a unified enterprise modelling language. Eventually, EM can be defined as the abstract representation of a business's structure, operations, procedures, data, resources, relationships (with all stakeholders), and all activities necessary to generate industrial goods or services [28].

Enterprise modelling approaches first surfaced in the 1970s as part of American (Identify, Credential, and Asset Management) or European (e.g., Computer Integrated Manufacturing Open System Architecture) programs, they were created as a result of businesses' need to have a thorough analysis of their operations. On the contrary, the field of system interoperability is relatively new, and the information systems domain was where its problems first appeared [29].

In 2004, Chen et al. [25] recognized enterprise modelling language as a fundamental research area contributing to develop interoperability. Indeed, the authors describe the relation between EM and interoperability of enterprise applications:

1. EM elaborates specifications to choose interoperable application and software on the market.
2. EM helps developing interoperability among heterogeneous applications and software.
3. EM elaborates specification to promote interoperable application.

Yet in 2006, Panetto et al depict the presence of several enterprise modelling methodologies and supporting tools, addressing phases of the enterprise life cycle and disparate aspects of enterprise modelling. In the same paper [64], some relevant methodologies are reported, highlighting their main features and criticalities (table 8).

Table 8 - Standards and Framework comparison [64]

Standard/ Framework	**Interoperability core features**
IEC 62264	Information structures and exchanges
ISO 10303	Representation of product information and exchange of product data
ZACHMAN	Intersection between roles in design processes and product abstraction
GERAM	Components used in all types of enterprise integration process
GRAI	Modelling with reference to functional abstraction and decomposition levels
ARIS	Development and optimisation of integrated information systems
CIMOSA	Concepts and models strictly necessary to model integrated enterprise systems
DoDAF	Understanding of the stakeholders and users needs
TEAF	Information from stakeholders and users alignment in business and IT
AKM	Layered Enterprise Architecture, POPS methodology, Enterprise Knowledge and Intelligent Infrastructure services
ISO 15745	Interfaces
MISSION	Distributed discrete-event simulation

Later, Kluza K. et al. [65] outline the lack of a unified model of process with rules to ensure data consistency. Starting from existing representation methods as the Business Process Model and Notation (BPMN) the authors extends these and integrate Business Rules (BR) obtaining a fully formalized model that can be used for the description of process models as well as for specification of integration issues addressing the consistency challenge.

A recent systematic study concerning the state-of-art and research on modelling languages has been conducted by Wortmann A. et al. [66] in 2020. The analysis revealed that the digital representation of Cyber-Physical Systems and all of its sub-systems is now the main area of Industry 4.0 concern. Several papers study and describe techniques as well as solutions, however it was noted a lack of validation research. Indeed, the latter was occasionally recorded, mostly concentrating on case studies or lab-sized systems.

In [52] the authors assert that semantical interoperability still needs to be addressed by modelling languages. Besides the existing works mentioned, there is still a lack of interoperability between conceptual modelling languages, simulation tools, and platforms for manufacturing systems. As a result, Gorecki et al. propose the use extant standards such as BPMN, HLA and FMI[2] as modelling tools and Distribute Simulation (DS) technologies to support interoperability among heterogeneous components operating across manufacturing systems. In a subsequent work [53], the authors consider the Papyrus (an open-source modelling and simulation tool) an efficient way to model and simulate industrial processes. Showing that the extension of Papyrus can be untied to other methods and technologies, Gorecki et al. demonstrate the possibility to add modelling and simulation components without impacting the basic model.

With reference to Kusiak and the UM paradigm, modelling languages for process and product modelling, are fundamental for the visibility of manufacturing systems (key to Universal Manufacturing). The author suggestions look at BPMS methodology as a candidate as well as the MTConnect standard and software [3], disclosed also in [67] [68].

[2] Functional Mock-up Interface (FMI) proposed as an open standard to support both Model Exchange (ME) and Co-Simulation (CS) of simulation models created with different toolchains. FMI has been adopted by several modelling and simulation environments [113].

4.6. Semantic and Ontologies

Significant complexity in inter-enterprise communication results from the mapped business processes and the semantics that must be taken into consideration. In fact, semantics play a key role in establishing a shared understanding of communications, which controls knowledge-sharing activities [30]. Semantic interoperability is defined as a common semantic interpretation of knowledge provided by the use of meta-models. In human-machine settings, the problem of shared knowledge meets several challenges. These include ontologies that represent various settings and fields of practice, multiple data formats, and various word meanings [31]. Therefore, semantic interoperability is achievable when the knowledge and information acquired can be efficiently communicated in a collaborative setting without any meaning or intent being lost in the process [69].

Many articles, in parallel with the semantic interoperability concern, discuss about ontologies, their usefulness and scope. An ontology represents domain knowledge in the form of a hierarchy of terms describing some domain, relations between these terms, and definitions that may be used to classify specific entities[3]. Indeed, ontologies are pointed out as semantic models that can formalize a great level of details supporting reasoning (making inferences and gaining new knowledge). They enable the acquisition, exchange and processing of information and knowledge based on their semantics [31]. Semantic information and models as a basis are required by every ontology in order to apply to data [70].

Therefore, an ontology can be seen as a formal conceptualization of a particular domain of interest which is shared among heterogeneous applications. Even though they were not often used for overcoming the interoperability problem, ontologies are now a well-proven tool to solve it. However, problems arise due to the independency of the stakeholders inside a network. Each of them works with terminology and formalism belonging to its own ontology. A key aspect under such perspective is the lack of a shared top-level ontology, potentially able to unify and organize different aspects of the field and manage the co-development of orthogonal ontologies [71].

The lack of semantic consistency neglecting data interoperability is well-known since the late 90s. One of the first solutions found in the literature throughout this analysis

[3] T. R. Gruber. A Translation Approach to Portable Ontologies. Knowledge Acquisition, 5(2):199–220, 1993.

is by Seo W. et al in 2006. In [72] the authors present a Reference domain ontology as well as a methodology for its building, aiming to support product data interoperability. The process consists of merging ontologies (manually) and it is one of the first layering process proposed in this domain. Indeed, subsequent literature next discussed stress on the efficiency and effectiveness about ontology reuse. For instance, almost ten years later, Ramos et al recognize that the majority of ontologies have been built from scratch discarding the ones previously developed. Moreover, these ontological approaches have frequent interoperability problems to some extent. In the study [73], the authors present an approach that combines ontology reuse, ontology validation, and ontology learning. Additional related proposals will be reported below.

In [49] Panetto et al. recognize that semantic interoperability constitutes an important approach to deal with heterogeneity within large and dynamic enterprises. Existing solution at the time were based on the use of standards as well as middleware software to tackle the problem. Nonetheless, such solutions did not record a high success rate as they neither do scale to large number of applications nor provide additional flexibility and agility. Similar conclusions are found in [74], in which Vujasinovic M. et al. point out the B2B communications' exclusive usage of proprietary data formats and messages, neglecting interoperability. Then, the authors address the problem proposing a semantic mediation architecture for standard base interoperability, which is described in a small-scale industry case. In particular, standard-based interoperability is said to be potentially achieved in three steps:

1. The establishment of a reference ontology by standard development organization (SDO)
2. The use of semantic annotation elements according to the business domain ontology (BOD)
3. The definition of reconciliation rules for the BOD.

In 2010, Liao et al., stating that interoperability is the basis of collaboration between enterprises, associate it to the possibility of easily exchange and utilize Knowledge Representation (KR) coming from disparate entities. But if lexical and syntactic issues can be considered as formally solved thanks to the use of standards [75], the establishment of a seamless semantic interoperability remains a huge challenge [76]. In fact, according to the authors, Enterprise systems and stakeholders must overcome two significant barriers in order to address the issue:

1. The implicit semantics that are essential for understanding a KR are not made explicit; and
2. the absence of an automatic semantic verification mechanism to ensure the accuracy of explicit semantics in a KR.

A deep investigation on the Semantic & Ontology topic is presented in [77]. Indeed, Negri E. et al., concentrate on the research of the best appropriate semantic languages for the development of manufacturing domain ontologies. The article contributes to such research field by proposing a broad literature review and analysing the available languages supporting the objective. The list of the ones studied is here reported:

- *KIF*
- *OntoLingua*
- *OCML (Operational Conceptual Modelling Language)*
- *Frame- Logic*
- *Loom*
- *DublinCore*
- *SHOE*
- *XML(S)*
- *RDF(S)*
- *OIL*
- *DAML*
- *DAML + OIL*
- *DAML _ L*
- *UML*
- *OWL*
- *C-OWL*
- *OWL Lite*
- *OWL DL*
- *OWL Full*
- *Context-OWL*
- *OWL-Eu*
- *OWL-E*
- *OWL Flight*

Overall, the findings relating to the candidate languages that could be used to model the manufacturing domain ontology are the OWL and its sub-languages: OWL Lite, OWL DL, C-OWL, OWL-Eu, OWL-E, as they satisfy all the requirements set by the authors (defined though a SLR):

- allow conceptual modelling and data storage
- offer easy use and maintenance of the model
- support interoperability
- support automated reasoning

Additional requirements and appropriate languages are said to be searched according to the specific application context and domain.

In [41] Szejka A.L. et al. advocate the need to share information across organizations to be competitive, identifying problems of misinterpretation and mistakes due to semantic interoperability obstacles. The cause is said to reside in different taxonomies used by disparate Product Design Processes (PDP) players, that build their specific information coding. Thus, through a systematic literature review the context is analysed from 2005 to 2015 to identify milestones and challenges present in the industry. In particular, three information interoperability issues have been identified:

- Information heterogeneity, originated by different domains
- Information associated to multiple phases of PDP
- Relationship between product needs or constraint and their characteristics (*completeness, coherency, uniqueness, univocity, verifiability and traceability associated with each of them*)

These findings show that the scientific academy must properly address the absence of semantic interoperability throughout PDP in order to assure accurate information and knowledge interoperability and to minimize misunderstandings and errors during PDP stages. Besides, poor literature about interoperability across multiple domains was found. It was verified that, until that time, the great majority of approaches proposed solved specific information exchange between domains. Eventually, the analysis suggests 14 articles as major references for the research scope, in which different proposals having potential to solve semantic interoperability problems are presented, however they lack a holistic perception [41]. For future works, the authors suggest the development of a conceptual framework to support semantic interoperability in the product design and manufacturing across multiple domains. Indeed, models and proposals to solve the multiple domain issue did not take long to appear.

For instance, in 2018, Zhang et al. advocate the relevance of communication standards and protocols such as OPC UA or MTConnect. However, if the former does not offer the information model aiming at CNC equipment, the latter address this category but lacks the ability of control by equipment [67]. Therefore, a technical architecture based on mapping is put forward with multiprotocol support capabilities, potentially able to cope with the semantic problems of intercommunication and interoperability.

In [31] Smirnov et al., analysing cloud and service-oriented systems, conclude that multi-aspect ontologies which preserve the internal ones would be the most suitable solution to solve the semantic interoperability issue. Following a literature review, a list of most diffused ontologies is mentioned: The mOSAIC ontology, OWL ontology and SLA. Still, the authors remark that the most promising approach involve the preservation of ontologies, building structures on the top of them. The main limitation acknowledged refers to the limited number of ontologies that could be integrated as creating the global level was a manual work.

Likewise, in [71], Hagerdon T. et al. highlight that most ontologies are specific for their scope, difficult to extend and to be interoperable with others. Nonetheless, the authors demonstrate that the use of Basic Formal Ontology (BFO) enhances interoperability of multiple engineering-related ontologies. They firstly recognize the presence of several upper-level ontologies, terminologies, and representations which have been developed as a result of past research, but their application in industry is still rather infrequent, while several problems are caused by interoperability concerns. Additionally, the utility of existing technical ontologies to a wider community is constrained by the fact that they frequently overlap, are not interoperable, and are unreadable by humans. Under this perspective, the paper remarks the utility and potential of ontologies also using a shared development principle combining prior works. This innovative method calls for the establishment of more conventional domain ontologies as well as suite-level semantic considerations to enable adaptation to other domains. The underlying principle used throughout the development is an independent expansion of expressiveness with extension of the ontology [71]. This encourages interoperability, while reducing the efforts required to construct ontologies, and makes it possible to use a small number of patterns consistently across domains. Overall, through the use of a Top-Level Ontology, taking advantage of existing ontologies developed with similar principles, it is demonstrated that even non-conformant domain ontologies can be integrated. Ontology reuse have been suggested as a promising practice also by other authors in the late literature.

Pereira et al. in 2020, highlighting the value of connecting and exchanging information across production systems, advocate for challenges brought on by various software tool database formats: semantic interoperability issues (misinterpretation and mistakes) related to information heterogeneity. Indeed, manufacturing industries utilize a wide range of software (SCADA, 3D CAD, CAM, ERP, MES etc.) which, individually, perform their function supporting the manufacturing process. In the paper [78], the authors address the problem with reference to the literature: possible solution may be developed through the application of semantic technologies. Indeed, compared to current industrial techniques, they have the ability to offer solutions that are more complete, and information may be shared across multiple domains. Therefore, to face the challenge, "semantic reconciliation" is described as a necessary process to realize. Also, in order to realize this process in a more automated environment, companies are investing in computational network emerging technologies, such as the Semantic Web [78] (*subsection 4.6.1*).

In [43] Polenghi et al. assert that intra- and inter-enterprise interoperability between systems is required to facilitate information management among several involved parties in order to reach operational excellence. In this regard, ontology engineering is acknowledged as important, promoting interoperability at the technical and semantic levels. Despite there are a number of recommended practices for ontology modelling, including knowledge reuse, the potential benefits of leveraging already existing information have not yet been fully realized, leading to an uncoordinated heterogeneous ensemble of ontologies. With regard to a maintenance and asset management environment, the study [43] does in fact intend to encourage the use of knowledge reuse for ontology modelling. Following a broad review to understand the state of art of ontology modelling, results show that reusing ontologies and ontological taxonomies is actually a well-mentioned practice with several recognized advantages:

- Less work is required for the creation of new ontologies, to formalize new ideas.
- Better quality as the repurposed components of the new ontology have previously undergone testing.
- Better mapping of ontologies that share similar concepts.
- Since shared and recurring concepts are modified just once, maintenance costs are reduced.

Overall, by depending on already tried-and-true ontological components, the reuse strategy ensures knowledge expansion or advancement in the field towards enhanced intra- and inter-enterprise interoperability at technical and semantic levels.

Later, Bitsch G. et al. [70] present, also through a use case, an approach to support the building of ontologies in the context of CPPS with reference to the ontology reuse practice above discussed. Indeed, this methodology demonstrates how several ontologies may be utilized concurrently, in contrast to earlier approaches that often concentrated on one particular ontology which was frequently available on one system component. In particular, while the classical development of an ontology is made from scratch-up, the framework is based on existing ontologies and their investigation according to different steps (table 9).

Table 9 - Approach for Ontology development and use [70]

Process Tasks	Information Technology
1) Identify and analyze use cases	1) Setting standards (language, communication)
2) **Scan existing Ontologies**	2) Build an Ontology-Repository
3) Choose, create, or adopt an Ontology	3) Implementing CPS specific semantic information
4) Evaluate Ontology	

As can be deducted from the table, the authors do not neglect the possibility to create brand new ontologies but recognize such case for very rare situation, given the wide presence of current valid ontologies. Indeed, if no comparable ontologies can be found, a new specific ontology shall be created. In addition, according to such methodology, the semantic information is not only provided centrally but in a decentralized way. As a result, CPSs and the CPPS system as a whole can be made more smarter and more transparent, facilitating decentralized coordination and adaptable configuration.

Recently, a reference architecture model allowing to solve semantic and syntactic interoperability problems (concerning the communication level) have been proposed by Rocha et al. Indeed, in [79] the authors focus on interoperability, through an Industrial Internet Reference Architecture (IIRA), among the IEEE 1451 and IEC 61499 standards in an industrial domain. Although focusing on a syntactic and semantic perspective, the proposed model falls even in the IoT-interoperability topic. Indeed, the presented standards are widely adopted in such context (*section 4.7*). In particular, the authors recognize the IEEE 1451 family of standards as relevant in order to facilitate the information exchange between smart transducers, building digital elements while the IEC 61499 standard as an enabler of control and automation, providing data to the framework layer of IIRA through the establishment of OPC UA, supporting semantic interoperability. Indeed, working on their combination at the syntactic level, it is asserted that the potential solving of interoperability issues. Besides, MQTT and HTTP (embedded in the application layer) can be exploited for the transport layer of IIRA. Some limitations can be identified looking at the of such communication protocols as the considered standards hardly communicate and interoperate with others used in industry 4.0. Nonetheless, being widely used, the combination of the IEEE 1451 with the IEC 61499 standards, enables data exchange through the reference architecture proposed.

Eventually, over the past years, tangible developments and improvements has been proposed and deployed throughout the different solutions aiming at addressing the semantic interoperability challenge. However, there is not a single model or strategy commonly accepted to solve the problem due to the widespread nature of the issue, which is present at several levels in the industrial setting.

4.6.1. Semantic Web

Obitko M. et al. [80] [81]define Semantic web as an expansion of the World Wide Web, in which information are described in a form suitable for software agents, given a clear meaning to improve interaction between machines and people. Through a survey, it is concluded that Semantic Web researchers are more concerned about potential interoperability in a heterogeneous environment than researchers in the manufacturing domain. The core semantic web technologies are Resource Description Format (RDF) and Web Ontology Language (OWL) [81]. Semantic web technologies are used to enable the adoption of semantics and ontologies simpler. In particular, semantic web attempts to establish a shared framework that would allow data to be shared and reused. Despite some differences, most of the research is immediately transferable to the manufacturing domain, serving as a source of inspiration for networked reconfigurable industrial systems.

Therefore, Semantic web can be seen as a network of relationships between entities [78]. However, its goal is to function as a virtual model of an item or process, so that any component—human or machine—involved may access the specifications that are being created in a shared environment. One of the key features of the Semantic Web is the systematization of knowledge, or interoperability, which is encouraged through ontological integration with the aim of producing a shared ontology for all sources of knowledge in a setting of information exchange.

In 2010, Cai M. et al recognize the development of semantic web technologies, supporting interoperability among distributed and heterogenous environments. Nonetheless, handling semantic differences across domain-specific Web services, such as manufacturing services, continues to be a challenge due to the lack of comprehensive vocabulary sets for characterizing them [82].

Panetto H. et al. [49] provide an overview of the necessity of enterprise integration and interoperability in manufacturing systems, describing trends and challenges significant for further study. The main issues are similarly connected to reference models, enterprise modelling, and their compatibility. The authors argue for the necessity of research to prevent corporate expenditures from being only driven by the IT industry's slow-motion growth as well as the lack of compatibility across enterprise systems. Besides, they assert that solutions based on semantic web services are seen as promising. Indeed, such technologies could provide solutions to the problem of semantic mediation and interoperation.

Indeed, in [77] the candidate languages that could be used to model the manufacturing domain ontology are the Ontology Web Language and its sub-languages. The latter serves as a semantic annotation for Web Services, enabling production system control based on the semantics embedded into the ontology.

4.7. Internet of Things

Internet of things (IoT) refers to the networking of physical and virtual entities over the internet. IoT is a key part of I4.0 and would certainly play a central role in the context of UM as it allows a wide range of services through information capture, data processing, and communication capabilities[4]. In this domain, interoperability refers to the ability of various IoT deployment components to efficiently interact, share data, and work together to achieve a common goal.

The literature recognizes a lack of interoperability with reference to the IoT context**,** neglecting the full exploitation of benefits from the market. A Mckinsey analysis points out that 40% of the potential benefits of IoT can be obtained with the interoperability between IoT systems. Indeed, IoT architectures are developed with the use of heterogeneous standards or even proprietary interfaces [32]. The European project Unify-IoT, identified the presence of more than 300 IoT platforms in the current market, and more to come. In particular, each of these platforms supports its own IoT infrastructure, proprietary protocols and interfaces, incompatible standards, formats, and semantics causing the development of closed ecosystems [83].

As a result, developing cross-domain platform or cross-domain applications is affected by interoperability issues. Following such problem, different authors proposed models and solution to tackle the challenge. Broring et al., [32] propose an architecture model, named BIG IoT architecture, to reach interoperability on the IoT. According to the authors, through clearly defined and agreed-upon data, interface formats, encodings, and information models (e.g., defined with ontologies) of the terms used as part of the interfaces and exchanged data, syntactic and semantic interoperability can be achieved. Similar to the multiple domain challenge discussed in the Semantic interoperability section (*4.6*), to enable an IoT ecosystem, interoperability frameworks shall establish the connection among more than two platforms [83]. In particular, the authors of [83] perform a comprehensive survey on the state-of-the-art (until 2019) solutions for supporting interoperability across different IoT platforms. Although the IoT standards, platforms and project investigated suggest advancement towards the interoperability challenge, some issues remain open as most of the proposals focus on the topic under a specific perspective.

[4] *Overview of the Internet of things: Y. IoT-overview*, ITU-T Y.4000, ITU-T, Jun. 2012.

Accordingly, Swamy et al. in [84] present an extended analysis about IoT, along with the current research trends in IoT technologies as of 2020. The authors report that the employment of disparate devices in terms of underlying communication standards and protocols, data formats, and technology makes interoperability a significant issue that persists [85]. Further causes behind such a challenge are identified: absence of common standard and rapid development of IoT applications. Concerning standards, table 10 shows the one adopted in IoT.

Indeed, IoT is a developing technology that lacks a specific central coordination or control [86]. Numerous standards and solutions have been produced and proposed from various viewpoints, but they do not in communication with each other and the is not an international agreed standardization ([87] [88]). In the current industrial environment, a remarkable trend deals with the integration of CPS along with the usage of IoT into the production processes of the manufacturing and logistic industries [89]. Accordingly, the interoperability concern reflects on Cyber Physical Systems and their inter-communication (*section 4.8*).

Table 10 - Standards adopted in IoT. Source: [112]

Technology	Standards
Communication	IEEE 802.15.4 (ZigBee) IEEE 802.11 (WLAN) IEEE 802.15.1 (Bluetooth, Low energy Bluetooth) IEEE 802.15.6 (Wireless Body Area Networks) IEEE 1888 IPv6 3G/4G UWB
RFID	RFID tag ISO 11784 RFID air interface Protocol: ISO 11785 RFID payment system and contactless smart card: ISO 14443/15693 Mobile RFID: ISO/IEC 18092 ISO/IEC 29143 ISO 18000-1 – Generic Parameters for the Air Interface for Globally Accepted Frequencies ISO 18000-2 – for frequencies below 135 kHz ISO 18000-3 – for 13.56 MHz ISO 18000-4 – for 2.45 GHz ISO 18000-6 – for 860 to 960 MHz ISO 18000-7 – for 433 MHz
Data content and encoding	EPC Global Electronic Product Code, or EPCTM EPC Global Physical Mark Up Language EPC Global Object Naming Service (ONS
Electronic product code	Auto-ID: Global Trade Identification Number (GTIN), Serial Shipping Container Code (SSCC), and the Global Location Number (GLN)
Sensor	ISO/IEC JTCI SC31 and ISO/IEC JTCI WG7 Sensor Interfaces: IEEE 1451.x, IEC SC 17B, EPC global, ISO TC 211, ISO TC 205
Network Management	ZigBee Alliance, IETF SNMP WG, ITU-T SG 2, ITU-T SG 16 IEEE 1588
Middle	ISO TC 205, ITU-T SG 16
QoS	ITU-T, IETF

4.8. Cyber Physical Systems

Cyber-Physical System (CPS) refers to a generation of digital systems which mainly focus on complex interdependencies across the cyberspace and physical world. Such kind of systems are composed by highly integrated computation, control, communication, and physical elements. CPS is currently of interest in academia, industry, and government [33].

In particular, CPSs are recognized to be core components of next-generation enterprises, comprising a heterogeneous mix of software as well as physical components, developed through the cooperation of different engineering disciplines and supporting collaborations [50]. Several powerful software tools are exploited by the different disciplines, but it is still difficult to combine these into tool chains for better efficiency [34]. Over the years, numerous authors addressed the challenge presenting solutions and approaches to manage it.

In 2017 Givenchi et al. [37] propose a middleware layer to achieve interoperability in the CPS domain, it would be established among the physical and the cyber system, through the application of a common information model (CIM). At the time, based on vendor-specific implementations, more than 25 industrial ethernet protocols were established and made available on the market. As a consequence, a multitude of interfaces and approaches to access the field of data was required. Related works and project are mentioned as the OPC UA, using the ISA95 standard or a middleware technology based on OPC. Nonetheless, the authors describe and test an interoperability layer acting as an intermediate, which maps data characteristics belonging to physical devices and components into a common information model that can be processed also by the cyber layer [37]. Concerning future study in this domain, integration of IoT-based platforms is recognized. Later, Gürdür et al. in [34] present a thorough analysis of literature concerning the interoperability discourse' with the goal of identifying valuable concept that may be used to the integration of CPS tool chains. The most important interoperability assessment models were described and analysed.

Table 11 - Interoperability assessment models [34]

Model	Which type(s) of interoperability the models focus on
LISI	Technological
OIM	Organizational
LCIM	Conceptual
SoSI	Programmatic, Constructive and Operational

Concerning these models (table 11), three issues limiting their utilization were identified:

- Complex metrics use
- Focus on particular aspects of interoperability
- Limited support for decision-making

Overall, the interoperability discourse's types and domains complement the CPS discourse's advice, which already specifies several application domains, engineering disciplines, governance, etc. In 2019 Burns et al. draw up a review of interoperability standards for industry 4.0 addressing also the Cyber Physical Systems interoperability matter. As exchange of data and information among CPSs is of paramount importance, semantic and ontology interoperability is equally fundamental. The authors recognize Semantic Web Technologies promising tools to approach this challenge. In particular, the Semantic Web of Things for CPS framework aims to achieve ontology alignment (thanks to the identification of semantic correspondences) by implementing multiple knowledge bases. So, through the merge of different ontologies, a knowledge base shall contain a repository of data about entities and their respective relations in different domains [90]. Nonetheless, a shortcoming relates to the requirement of significant user input, as the knowledge base system needs to be updated by users, in order to develop interoperability. Incorrect information might also be inserted into the knowledge base, causing issues for the end user.

The research about CPS interoperability is a rather recent endeavour. Indeed, in 2020 Panetto et al. define some pathways representing the different stages for implementing Interoperable Cyber-Physical (Production) Systems [91]. Therefore, the authors employed a technique known as “pathways” to map many potential paths for Enterprises (and Researchers) to a vision for Interoperable Cyber-Physical Systems. The outcome can be considered as a potential input for a scientific foundation concerning the enablement of loose integrated (interoperable) cyber physical systems [91]. A remark is made upon organizational aspects, production technologies as well as physical production processes to be considered in future research, without the exclusive focus on information and software systems perspectives.

Recently, Cohen et al. presented a smart supervisory framework for a single process controller, designed for Industry 4.0 shop floors, within which the interoperability matter is addressed by a "gateway" component (see figure 9). As the application of the suggested framework, implemented as a unified control solution, generates a rich cyber physical entity of the regulated process, it is consistent with the idea of a Cyber Physical System (CPS). In this situation, interoperability, data/information, representation, and interchange format challenges are related to the single controller's interface with the external digital world. [92]. Indeed, the model comprise an external interaction module to support interactions, solving interoperability issues.

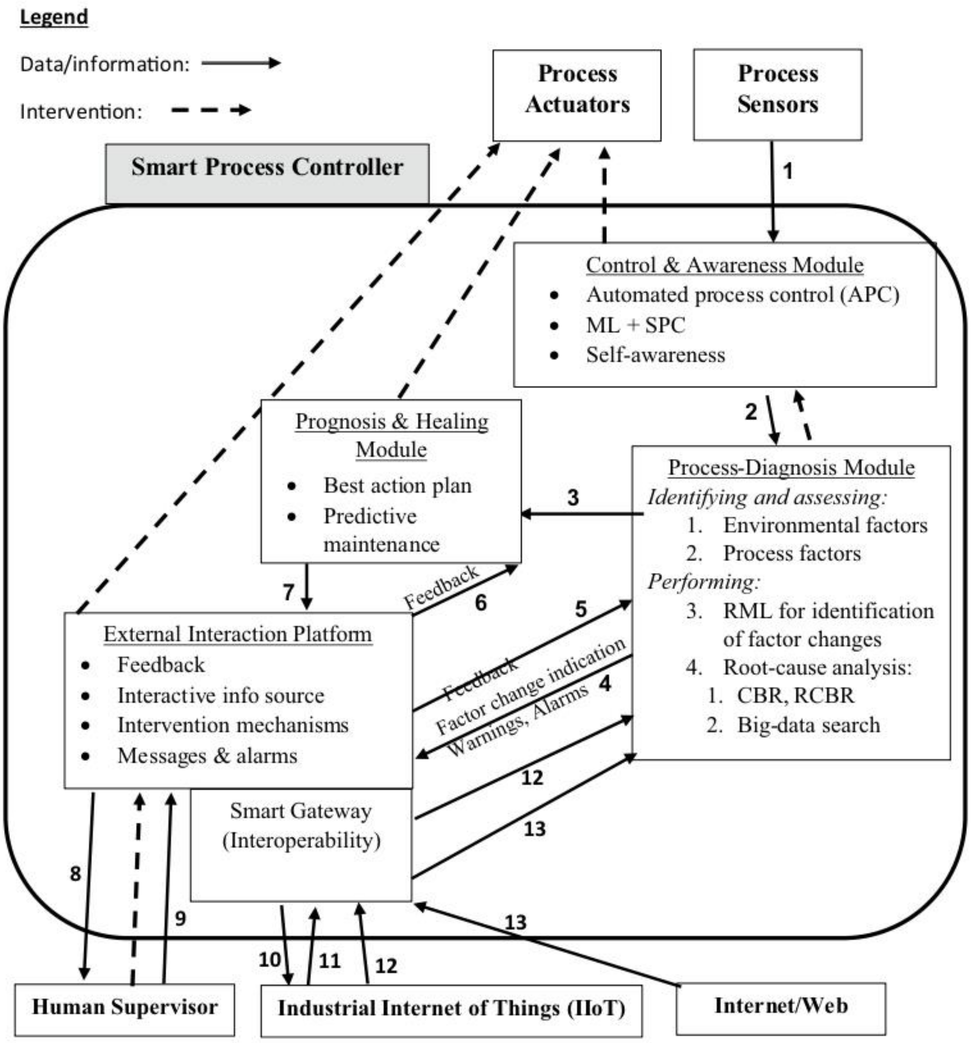

Figure 9 - The proposed smart process control framework and its main elements. Cohen et al. [92]

In particular, data arriving from devices (e.g., sensor or other elements) are pre-processed in the *control and awareness module* in order to guarantee format compatibility as well as a proper handling of the collected data. As syntactic and semantic issues may arise from the communication with external entities, these interactions are treated by means of the gateway. The latter must embed a software that able to process and translate the most prevalent IoT standards (*e.g., OPCUA (Open Platform Communications Unified Architecture*) *and MQTT* (*Message Queuing Telemetry Transport*)).

4.9. Trust & Security

The intensification of cooperation, exchanges of data and information among enterprises and their partners, along with the interoperability development, led to another trend: to integrate the concept of trust besides the concept of collaboration in the new Enterprise Architecture frameworks [17]. Indeed, organizational trust is a crucial notion that must be assessed and controlled as it directly influences the degree of integration in horizontal relationships, the quality of collaboration, the type of alliances, and the quality of IT solutions used in interfirm cooperation [93] [94]. Trust is here intended as a function of the partner's reliability, behaviour, and commitment.

Accordingly, such a concept is here discussed together with security issues that may arise during collaborations among enterprises. Indeed, enterprise networking requires businesses to openly share services across Internet infrastructures, expose their information systems, and exchange a lot of knowledge and information [20]. According to the Ponemon Institute[5] (2021), in the past two years, more than 90% of industries have seen at least one significant malicious cyber-attack, including systems that use IP-based connection, industrial control systems, and supervisory control and data acquisition [95].

In [96] Yang et al. address workflow systems' security issues recognizing the limitation of the traditional workflow authorization in handling changes and exceptions. The authors propose a flexible access control framework to manage such cases in a dynamic business environment. The presented model satisfies the authorization requirements both in a static and dynamic environment. Next, the prototype is applied on a case study followed with an explanation of the three modules to be implemented. Security issues can be considered as an always present concern in relation to the analysed literature. Indeed, in a more contemporary paper and from a CPS perspective, Ferrer et al. [97] present two techniques to overcome the current solutions looking at the interaction among machines and humans (through semantic technologies) since, as recognized by the authors, are sporadically validated in terms of security. The proposals correspond to threat modelling and risk assessment in order to protect semantic-based approaches from malicious access and attacks. These techniques are also applied and illustrated within a case study.

[5] https://www.trendmicro.com/vinfo/us/security/news

Overall, in the years just afterwards, the issue of trust advocated by Vernadat F. in [20] was little discussed. An interesting proposal towards this matter is disclosed in [98], in which Xu et al. claim the role of Blockchain smart contracts as a viable solution, fitting in the IoT environment, capable to establish trust of process without intermediaries. Indeed, for the development of automation and intelligence in the Internet of Things, Blockchain has shown a great potential in the establishment of data security and trust. Numerous studies have been conducted in this direction. In particular, Blockchain can serve two fundamental roles in order to provide trust of data from its secure storage and trust of process executions, which may ensure that activities are carried out truthfully across participants [98]. Significant impacts have also been investigated in the Supply Chain field where Blockchain technologies offer huge potential to acquire data across the network, enhance traceability and visibility among the different stakeholders thus, providing real-time tracking to authenticate the identity while preserving intermediaries' privacy and security [99]. Indeed, the conceptual framework proposed in [99], based on Blockchain technology and IoT, aims at enhancing interoperability as well as digital document transactions facilitating product traceability and transparency. The study by Wanganoo L. et al. adds to the theoretical and applied literature on cross-border e-commerce, reverse supply chain management, document reversal, re-export issues, and how the application of Blockchain technology may help enterprises to overcome such difficulties in a highly competitive environment. [99].

Besides blockchain technologies aiming at achieving trust during the exchange of data and knowledge, other methods focus on machine integrity and CPS security. Mehdi et al [100] work contributes to solving the crucial problem of identifying and authenticating industrial units in the digital environment. In the paradigm of network-connected devices, the study offers an effective yet reasonably straightforward technique for machine registration and authentication from their physical attributes. Jhon J et al. [101] introduce a declarative policy layer using CP-ABE[6], an advanced security mechanism for middleware platforms, to address security risks in a smart manufacturing and IoT-connected context. Zografopoulos et al. [102] provide a comprehensive analysis of CPS security, recognizing such connected architecture as the backbone of an enterprise. Accordingly, the authors assert how CPSs are frequently the subject of malicious assaults intended to obstruct their operations due to their critical nature, potential interoperability, and variety of computer devices. Next, they

[6] Ciphertext-Policy Attribute-Based Encryption

present a framework capable to delineate all the CPS components as well as modelling resources to simulate and assess performance under adverse scenarios.

Overall, there is a strong focus on research, initiatives, and adaptation of solutions from disparate areas. Still, the achievement of a complete trustworthy interoperability is a challenge [95]. Indeed, in a recent article, Allian et al. investigate and define a set of requirements for ensuring a trustworthy interoperability in the industry 4.0 domain. In this context, the suggested drivers might be seen as a first step for designing appropriate and comprehensive solutions. A relevant finding is that considering a single quality aspect as security or privacy is not enough to assure its realization. In fact, according to the authors, it is necessary to consider the combination of seven specific quality concerns, or drivers, which are shown in table 12. Such requirements have been collected from the literature as well as by experience, judgments, and challenges faced by experts in an industry 4.0 context. The presented drivers are aligned to real-world interoperability needs in current industry projects [95]

Table 12 - Seven architecture drivers to promote trust in interoperability in Industry 4.0. [95]

Driver	Description
Authentication to the system	Explains the procedure for verifying and guaranteeing that users and devices are identified. Devices, servers, gateways, and other stakeholders all need to be authenticated in order to access the system. The application must provide a reliable means to enable the insertion and removal of new devices because it is a constantly evolving system.
Data access control	Refers to the access rights that a user is given to large amounts of data, preventing the unauthorized sharing of sensitive information. The access permissions that various stakeholders and devices have to the manufacturing line must be appropriately handled.
Data privacy to protect sensitive information	Focuses on the anonymization of data for organizations who have contracts to comply with privacy-related legal requirements in order to create goods in a production line. Potential clients must have access to specific data in a production as a service scenario. They cannot, however, access information about goods purchased by other consumers.
Traceability and auditability of data	Explains the capability of supporting an audit trail and tracking data in the event of a malicious attack. This driver addresses both the auditability and traceability aspects by logging who started changes, in which way, to the autonomous decision engine, and the plant engine.
Availability of physical devices	Relates to the availability of all pertinent information in real time. Physical data redundancy is typically used to do this; in the case of an unanticipated incident, the other copies can still supply the data.
Availability of data	According to the existing obligations in the manufacturing domain, it states that manufacturers must keep records and logs of their production lines for a minimum amount of time. Sponsors must be able to access this information upon request or for auditability verification.
Compatibility of data and services	Refers to the capacity to scale Industry 4.0 production when a new external device is integrated into a manufacturing structure. In a modern Industry 4.0 system, compatibility is needed to connect, translate, and utilise data across many machines. This driver illustrates such situation.

5. Discussion

The performed Systematic Literature Review about interoperability within the context of UM supports the definition of the state-of-art as well as of current gaps in the manufacturing domain. The establishment of Industry 4.0 has brought several challenges concerning the need to acquire and integrate large amounts of data from heterogeneous sources [103]. From this perspective, interoperability is advocated by the literature as a crucial aspect to meet these issues. Besides, the potential advent of Universal Manufacturing would enhance even more such perspective, looking for seamless interoperability across devices, processes and data.

The content analysis shows substantial signs of progress concerning each category of the framework. Many valid languages exist in the domain of Enterprise Modelling and recent works integrate disparate modelling and simulation tools. Indeed, Kusiak (2021) describes BPMS methodology as a candidate as well as the MTConnect standard and software for the UM roll-out. Several solutions have been proposed for semantic interoperability also in a multi-domain context, while ontology reuse and semantic reconciliation seem to become more and more recognized as promising techniques. IoT adoption is increasing within Industry 4.0 and while architectures have been proposed to make platforms and protocols interoperable, the integration of different standards in this domain is currently being researched. Middleware is being implemented to achieve interoperability among CPSs. From a perspective of trust, besides Blockchain technology, meaningful drivers have been investigated and described for the design of appropriate and comprehensive solutions.

Overall, the research community shows a strong interest towards solutions for the achievement of interoperability. Indeed, many authors' works have been presented throughout the analysis, by describing models, frameworks, software, etc. However, a persistent challenge is evident: a lack of a universal shared and agreed-upon solution for each of the various areas analysed. In addition to the heterogeneity challenge described in section 4.1, the constant evolution of technology hampers to predict interoperability requirements for future technologies [104].

The following arguments are taken from the most recent eligible papers in order to give a well-documented overview of the late literature concerning interoperability:

- In relation to trust & security, Blockchain seems to be a promising solution from this perspective however, as Liu et al. note, "*it is very challenging to enforce correct executions in a full trust-free manner where no trusted authority is allowed to coordinate the executions on different blockchains*" [105]. Interoperability has been made possible by important recent developments in this field but there is still a gap between theory and practice as most of the current research is conceptual [106]. Accordingly, Allian A. assert that Trustworthy interoperability across heterogeneous systems and companies remains a great challenge [95].
- As regards IoT, protocols and heterogeneous platforms currently pose interoperability issues due to such a diversity [107]. One significant challenge in this area includes a framework for IoT applications to interact and interoperate with sensors. Mirani A. et al. et al assert that "*As Industry 4.0 is currently in its initial phase of development with the integration of Industrial IoT, the current literature needs to focus on interoperability for the efficient utilization of resources through machine-to-machine (M2M) communication*" [108].
- In a 2022 dated article, Melluso et al. [103] propose a quantitative approach looking at the enhancement of interoperability across I4.0 standards. Previous works recognized a constantly increasing number of standards as well as the need of a suitable infrastructure to collect and deliver knowledge [109].
- Kiesel R. et al. [59] in 2021 assert that the necessary integration of CPPS and Enterprise software leads to extant technological obstacles. Further, because of a lack of semantic interoperability, also data sharing across domains still presents documented problems.
- Organizational interoperability has not been investigated in this review as few information was obtained by the SLR implementation. However, Kolagar et al. in 2022 [110] state that a key challenge for manufacturers is to adapt strategies, culture and management practices with one of their partners leading to cooperative failures within an ecosystem.

Overall, numerous solutions were outlined and capable of answering to the interoperability quest in disparate areas. Universal accepted standards or framework are still missing but the industry is gaining more and more interest towards the topic. Efficiency and effectiveness would be immediately perceived by all players throughout the entire supply chain. To speed up the progress, a cooperative strategy is required for the development and establishment of Universal Manufacturing [16].

6. Conclusion and future developments

This research work stems from the innovative concept of Universal Manufacturing conceived by A. Kusias (2021). Enablers and currently outlined properties of UM have been briefly described. Among them, Enterprise Interoperability was selected to carry out a literature analysis about the state-of-art and challenges advocated by authors and researchers. A description of interoperability according to the EIF was presented with a focus on the three types of interoperability: Technical, Semantic, and Organizational. Interoperability in industry 4.0 refers to collaborations between physical and virtual entities, producers, and stakeholders across growing-size supply chains. Next, the concept has been deepened throughout a systematic literature review.

The application of SLR supported the answering of the two research questions: (i) *What is the state-of-art of industrial interoperability with a view to universal manufacturing?* (ii) *Which challenges about interoperability are recognized by the literature?* The content analysis explored the interoperability concept by looking at three different models/approaches (Federated-, Middleware-, and Model-driven-Interoperability) and five areas of applications/research (Enterprise Modelling, Semantic & Ontologies, IoT, CPS, and trust & security). Undoubtedly, the quest for interoperability is now of great interest among the research community in the manufacturing domain.

Likewise, the heterogeneity challenge is highly recognized in the industry-related literature as a significant obstacle to overcome. Several proposals have been outlined, potentially capable to establish interoperability in different contexts. Among the numerous existing modelling languages and standards, valuable solutions can be found, such as MTConnect but wider adoption is still needed. Although several authors' works have been presented, including models, frameworks and applications, there is a lack concerning a universal accepted and shared solution for each of the various areas analysed.

Significant signs of progress have been made in the interoperability context, especially in relation to the communication layer across multi-domain systems. Nonetheless, interoperability does remain a characteristic that enterprises investigate and want to achieve.

A limitation of this work resides in the broad scope of Enterprise interoperability. Indeed, additional fields, intended as approaches and areas of applications, could be investigated such as interoperability in the Cloud, for Digital Twins technology, and Organizational interoperability. Additional keywords and Boolean operators can be evaluated in future reviews.

Referring back to Kusiak A., the conceiver of UM, based on the analysis of industries, several characteristics of Universal Manufacturing can be spotted in many corporations [16]. This work can be considered as further evidence. To speed up the progress, a cooperative strategy is required for the development and establishment of Universal Manufacturing.

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List of figures

List of tables