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E DELL'INFORMAZIONE

Scheduling for Sustainable Manufacturing: a methodology proposal

TESI DI LAUREA MAGISTRALE IN
MANAGEMENT ENGINEERING-INGEGNERIA GESTIONALE

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Abstract - English

The development of a more economically, socially, and environmentally sustainable society is one of the greatest and most urgent challenges of the 21st century. The manufacturing sector plays a key role in achieving the goals of sustainable development, at a time when the industrial revolution dictated by the new Industry 4.0 technologies is a powerful tool available to companies. In this context, there is growing attention in the academic world toward the inclusion of energy and resource management considerations in scheduling problems. With the systematic literature review carried out in this thesis, the aim is to offer an examination of the application of sustainability concepts to scheduling problems and to investigate how decision-making at the scheduling level can support the achievement of improved sustainability performance in a manufacturing system. The 52 articles found are classified in a research framework according to the machine environment adopted, the type of optimisation proposed, the performance and sustainability metrics used, and the inclusion of Industry 4.0 technologies. Among the gaps, it emerged that there are limited approaches in which several environmental sustainability metrics are taken into account simultaneously in the model. For this reason, a methodology is proposed for setting up a scheduling problem that includes an overall assessment of environmental sustainability performance. The proposed approach involves the identification of appropriate metrics dependent on scheduling decisions that are then aggregated into a single indicator to be included in the objective function of the optimisation problem.

Key-words: Sustainability, Manufacturing, Production Planning, Sustainable Scheduling, Green Scheduling, Methodology.

Abstract - Italian

Lo sviluppo di una società più sostenibile dal punto di vista economico, sociale e ambientale rappresenta una delle più grandi ed urgenti sfide del ventunesimo secolo. Il settore manifatturiero gioca un ruolo chiave nel raggiungimento degli obiettivi di sviluppo sostenibile, in un momento in cui la rivoluzione industriale dettata dalle nuove tecnologie di industria 4.0 rappresenta un potente strumento a disposizione delle imprese. In questo contesto vi è una crescente attenzione del mondo accademico verso l'inclusione di considerazioni sulla gestione dell'energia e delle risorse in problemi di scheduling. Con l'analisi sistematica della letteratura effettuata in questa tesi si vuole offrire una disamina dell'applicazione dei concetti di sostenibilità ai problemi di scheduling e indagare come il processo decisionale a livello dello scheduling possa supportare il raggiungimento di migliori prestazioni di sostenibilità in un sistema manufatturiero. I 52 articoli trovati sono classificati in un research framework in base alla configurazione delle macchine adottata, il tipo di ottimizzazione proposto, le metriche di performance e sostenibilità utilizzate, la trattazione del tema di industria 4.0. Tra i gap è emerso che sono limitati gli approcci in cui diverse metriche di sostenibilità ambientale sono tenute in considerazione contemporaneamente nel modello. Per questo motivo è proposta una metodologia per l'impostazione di un problema di scheduling che includa una valutazione complessiva delle prestazioni di sostenibilità ambientale. L'approccio proposto prevede l'identificazione di opportune metriche dipendenti dalle decisioni di scheduling che sono poi aggregate in un unico indicatore da includere nella funzione obiettivo del problema di ottimizzazione.

Parole chiave: Sostenibilità, Manifattura, Pianificazione della Produzione, Scheduling Sostenibile, Metodologia.

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1. Introduction

Drivers such as population growth, natural resource scarcity and an increasing number of observed environmental issues are making the topic of sustainability more and more important nowadays. The manufacturing sector is of strategic importance in achieving sustainable development goals for each of the sustainability pillars, namely economic, social and environmental. This is confirmed by the increasing attention of the academic world toward sustainable manufacturing. To achieve sustainable production the focus can be placed on the system, the process and the product, which need the development of improved models, evaluation metrics and optimization methods as tools for realizing sustainability in manufacturing. Scarce resource management and carbon footprint reduction have become important issues, particularly in production planning [1]. This is the focus of this thesis which aims at exploring what improvements can be made to the sustainability of the manufacturing processes through Sustainable Scheduling and Industry 4.0 technologies. This represents one of the six major research themes in Sustainable Manufacturing [2].

Scheduling is a decision-making process that is regularly used in many manufacturing and services industries. In manufacturing systems, it deals with the allocation of machines to operations over given time periods, and its goal is to optimize one or more objectives. A scheduling problem is traditionally defined by the machine environment, the details of processing characteristics and constraints, and the objective to be minimized [3].

2. Research Question Definition

Among all the stages of production planning, scheduling in Sustainable Manufacturing (also defined as **Sustainable Scheduling** or **Green Scheduling**) appears to be the most frequent research subject [4]. To offer a deeper understanding of the application of sustainability concepts to scheduling purposes and to investigate how the decision-making process at a scheduling level can support the achievement of better sustainability performance in a manufacturing system the following research questions have been formulated:

RQ1: How a scheduling problem in Sustainable Manufacturing is defined?

RQ2: What are the sustainability metrics currently used in Sustainable Scheduling problems?

RQ3: What are the applications of Industry 4.0 enabling technologies in Sustainable Scheduling?

3. Systematic Literature Review

A systematic literature review was conducted to answer the identified research questions. The research has been conducted using the SCOPUS database using the keywords "Sustainable Scheduling" OR "Green Scheduling" searching within the Article title, Abstract, and Keywords. As a result of the first research, the SCOPUS database gave 164 documents. A total number of 52 papers have been included in the analysis after the application of the exclusion criteria and after the cross-reference snowballing phase. The results of the systematic literature review are included in a research framework [p. 69/70].

3.1. RQ1

Through the first research question, the characteristics that traditionally define a scheduling problem were analysed. It emerged the heterogeneity of the analyzed machine environments and the usage of a variety of algorithms and methods that still retains the traditional objective of allocating resources to tasks by optimizing functions mainly related to completion time. The most widely used metric in accomplishing this objective is the makespan. Most of these problems use multi-objective optimizations to take into account more aspects of sustainability at the same time.

3.2. RQ2

Different metrics currently used in Sustainable Scheduling problems have been identified. Most are attributable to the environmental dimension of sustainability i.e., energy consumption, carbon emission, defective products, solid and liquid waste produced, water-related metrics and Life Cycle Assessment for environmental impact. Sometimes these metrics are translated into their economic equivalent i.e., energy cost and taxes on carbon emission. Among the social sustainability, the metrics used are noise pollution and accident rate. The papers considering energy consumption are by far the most frequent.

3.3. RQ3

Among the 52 selected articles, 7 articles refer to Industry 4.0 in the discussion. From the articles, it emerges that various Industry 4.0 technologies can potentially contribute to the goal of sustainable scheduling. These include cloud computing, edge computing, IoT, big data, robots, and digital twin. These technologies enable real-time data availability, scheduling, and rescheduling.

Given the few articles available that directly address the topic of Industry 4.0 and Sustainable Scheduling, for this research question, the search was expanded through citation analysis of the selected articles, and additional Scopus searches. It emerged that there are several studies in the literature about scheduling and Industry 4.0, but the topic of environmental and social sustainability still appears to be little addressed.

4. Gaps Identification

The systematic literature review conducted on Sustainable Scheduling gathers various information that is useful in defining the gaps and possible future research directions. What emerged from the analysis of the different sources with reference to the three research questions formulated is summarized in Figure 1.

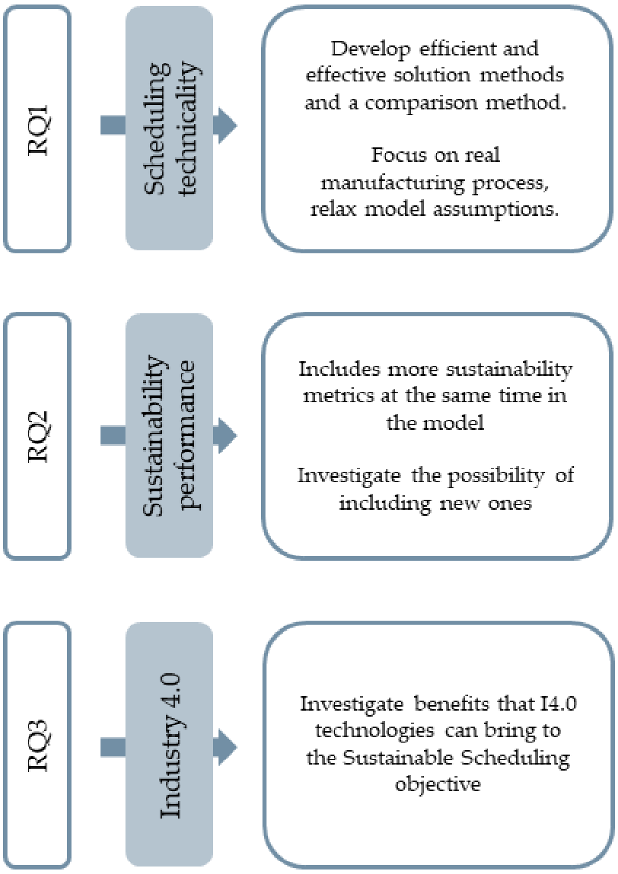

Figure 1. Future research suggestions from the literature review

5. Methodology Proposal

Starting from the gaps identified through the second research question it is proposed a methodology for the overall assessment of environmental sustainability performance in a Sustainable Scheduling problem. The objective of this methodology is to provide a useful tool for setting up a scheduling problem that aims at optimizing an overall assessment of the sustainability performance of manufacturing processes. The methodology is suitable for economic and environmental assessment, aiming to generate greater economic value and produce lower environmental impact. It is intended to be suitable for application in real manufacturing processes by selecting and classifying appropriate environmental sustainability metrics that can be affected by scheduling decisions. The proposed methodology consists in 6 steps described below.

1. **Case Study Selection and Analysis**; the first step is to select and analyze the characteristics of the manufacturing process of interest. It is indispensable to know the process and its peculiarities since these characteristics have an impact on the Sustainable Scheduling problem.
2. **Decision Variables definition**; the identification of those decision variables that may have an impact on the scheduling optimization problem and environmental sustainability performance. Those identified, in addition to the traditional decision regarding the allocation of machines to operations, are: *variable machine speed* and *machine on-off decision*
3. **Machines State Modelling**; more detailed modelling of the behaviour of the machines that constitute the manufacturing process. This provides a better insight into the behaviour of the machine and its environmental sustainability performance. Depending on the state the machine is in, resource utilisation can vary considerably. A possible example of finite state machine modelling is shown in Figure 2

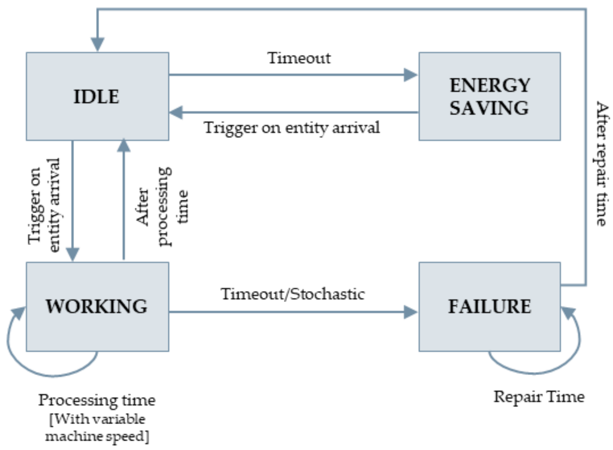

Figure 2. Representation of a finite-state machine model for Sustainable Scheduling

4. **Sustainability Metrics definition**; a pool of suitable metrics for environmental performance assessment in Sustainable Scheduling has been identified through the literature review. Those have been elaborated and classified into 3 categories:

- The **energy** category includes *Energy Consumption (E [kWh])* and *Percentage of renewable energy (E_{ren} [%]);*
- The **waste** category includes *Solid waste produced (SW [kg/min* or *kg]), Liquid waste produced (LW [kg/min or kg])* and *Defective Rate (Q [%]);*
- The **water** category includes *Water intensity (WI [m^3/min])* and *Percentage of water reused (W_{reu} [%]);*

The decision variables, machine states, and metrics proposed are strongly interrelated with each other and were defined to consider the environmental sustainability dimension relevant to scheduling problems.

5. **Approach definition**; the objective is to aggregate the identified low-level metrics into a key performance indicator that gives an overall indication of the environmental impact of the process. This metric is intended to be included in the objective function of a Sustainable Scheduling problem. Figure 3 shows an outline of the proposed approach for the overall assessment of the sustainability performance of a manufacturing process in scheduling problems.

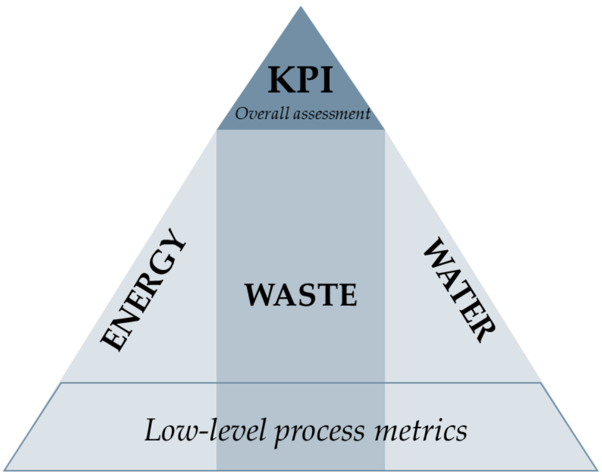

Figure 3. Approach to assess overall sustainability performance in scheduling

Two approaches are proposed in this thesis:

- **Carbon footprint approach**, where through a conversion factor is computed the mass of carbon dioxide equivalent (CO_2e) for each of the proposed metrics which are then added together to give an overall assessment of the process emissions;
- **Resource cost approach,** where the consumption of resources is multiplied by their unitary cost, which are then added together to give an overall assessment of the economic impact of the different environmental performances.

Following the logic of these two approaches, it is possible to develop others that use a different key performance indicator for the overall assessment of environmental performances

6. **Scheduling model development**; as the final step, the metric defined for the overall assessment has to be included in the scheduling model. Through a multi-objective formulation, it is possible to evaluate both the performance of the process in terms of efficiency (e.g., through makespan) and in terms of the environmental impact. The analysis of the resulting trade-off can guide companies in their decision-making process, selecting the production schedule that satisfies their objectives.

6. Conclusions

From the systematic literature analysis, it emerged that there are few studies that discuss scheduling problems that aim at assessing and optimizing more than a few sustainability metrics. This methodology provides a tool for setting up a scheduling problem that aims at optimizing an overall assessment of the sustainability performance of manufacturing processes. The methodology is designed to capture peculiarities of real manufacturing processes in terms of environmental sustainability, to be flexible and capable of synthesising sustainability performance into a metric to be optimised in line with the organisation's objectives. The methodology has limitations, namely, the exclusion of the social dimension of sustainability in the assessment, the need to have a lot of process data available, as well as difficulties with the mathematical modelling and the combinatorial optimization of the problem. These limitations leave the way open for several future developments, the main one being certainly the practical application of the model through the formulation of a Sustainable Scheduling model accordingly to what has been proposed and defined by the different methodology's steps

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1. Research Context

This chapter aims to provide an overview of the main scientific areas of interest in this thesis, which are:

- Sustainability with focus on Sustainable Manufacturing
- Industry 4.0 due to the key role it has in Sustainable Manufacturing
- Production planning with focus on scheduling for manufacturing processes

1.1 Sustainability

Drivers such as population growth, natural resource scarcity and an increasing number of observed environmental issues are making the topic of sustainability more and more important nowadays. The importance of sustainability-related issues in the current research agenda is underlined by the effort that the European Commission has placed in encouraging several research projects [1]. How to address sustainability issues is "one of the most significant translational research problems of our time" [2].

The sustainability concept has been formulated for the first time in 1972 in Stockholm during the Human Environmental Conference, being the first conference to consider the environment as a major issue. During this conference, it emerges for the first time the linkage between economic growth, environmental safeguard, and people's well-being [3]. In 1987 the concept of sustainable development was introduced with the Brundtland Report by the UN World Commission on Environment and Development as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [4]. Starting from that moment hundreds of definitions have been proposed in the literature with respect "to a more humane, more ethical and more transparent way of doing business" [5].

The increasing attention toward sustainability translates into different actions on a global scale. One of the most important regard the Sustainable Development Goals (SDGs) adopted by the United Nations in 2015 through the definition of 17 Goals (Figure 1.1), as part of the 2030 Agenda for Sustainable Development. The final aim is to promote prosperity while protecting the planet through a call for action for the development of effective strategies regarding economic growth, social needs, and environmental protection [6].

Figure 1.1: 17 Goals for Sustainable Development [6]

The Sustainable Development Goals Report 2020 shows how the change to achieve the goals was still not happening at the required speed even before the COVID-19 pandemic. This catastrophic event slowed down the process even more due to unprecedented health, economic and social crisis which require now more than ever a coordinated and comprehensive international response and recovery effort [7].

Another important global action for sustainability consists of the Paris Agreement adopted in 2015 by 195 parties. In the context of sustainable development, the involved parties commit themselves to mitigate climate change by holding the increase in the global average temperature below 2°C above pre-industrial levels (but preferably below 1.5°C) and pursuing a development made of low greenhouse gas emissions with consistent financial flows [8]. To maintain the temperature below the threshold of 1.5°C it is required to reduce greenhouse gas emissions by 35% by 2030 and to reach net-zero emissions by 2050. But again, commitments made by governments to date fall far short of what is required [9]. Looking at the trend of CO2 emissions worldwide in Figure 1.2 it's possible to notice that it is constantly growing [10] despite a slight slowdown in recent years probably due to the restrictions from the COVID-19 pandemic.

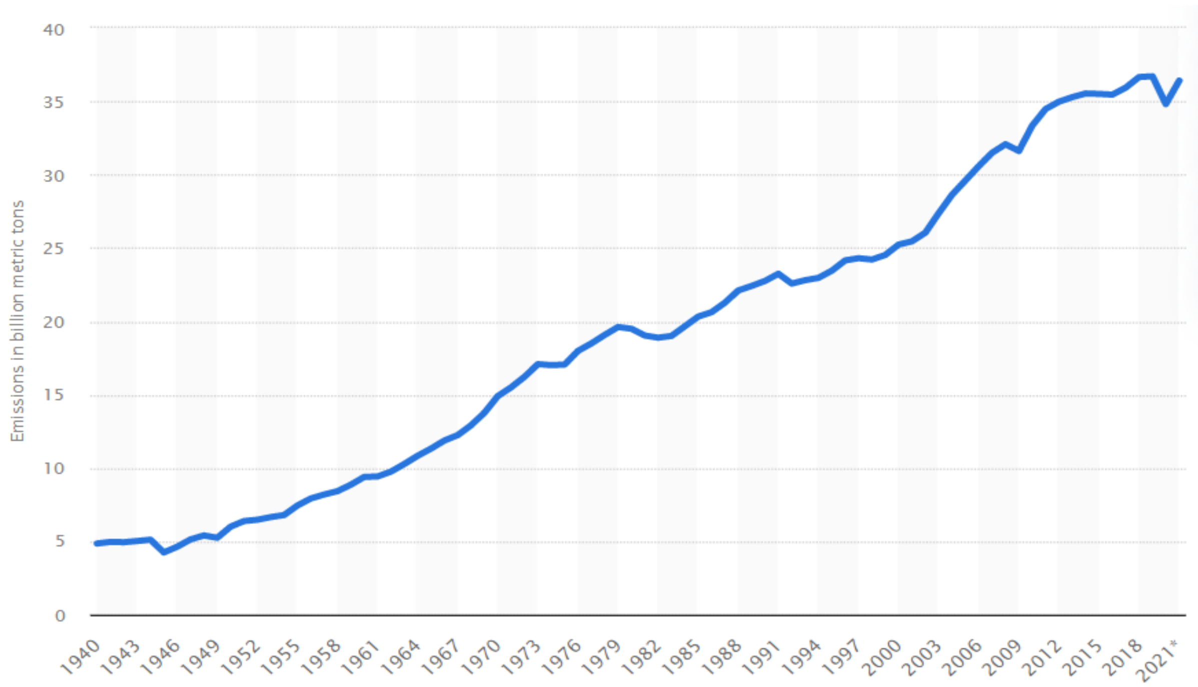

Figure 1.2: Annual CO2 emissions worldwide from 1940 to 2020 [10]

The concept of the three pillars of sustainability (social, economic, and environmental) has become ubiquitous in current literature and is also known as the Triple Bottom Line paradigm [11]. This concept is usually represented in the form of three intersecting circles as shown in Figure 1.3. Each circle represents a sustainability pillar, with sustainability itself placed at the intersection [12]. An alternative representation is the "Three P's" which stand for People, Profit, and Planet that are represented again as three intersecting circles with sustainability placed at the intersection as shown in Figure 1.3. Both sustainability representations aim at being a transformation framework for businesses and other organizations to help them move toward a regenerative and more sustainable future [13].

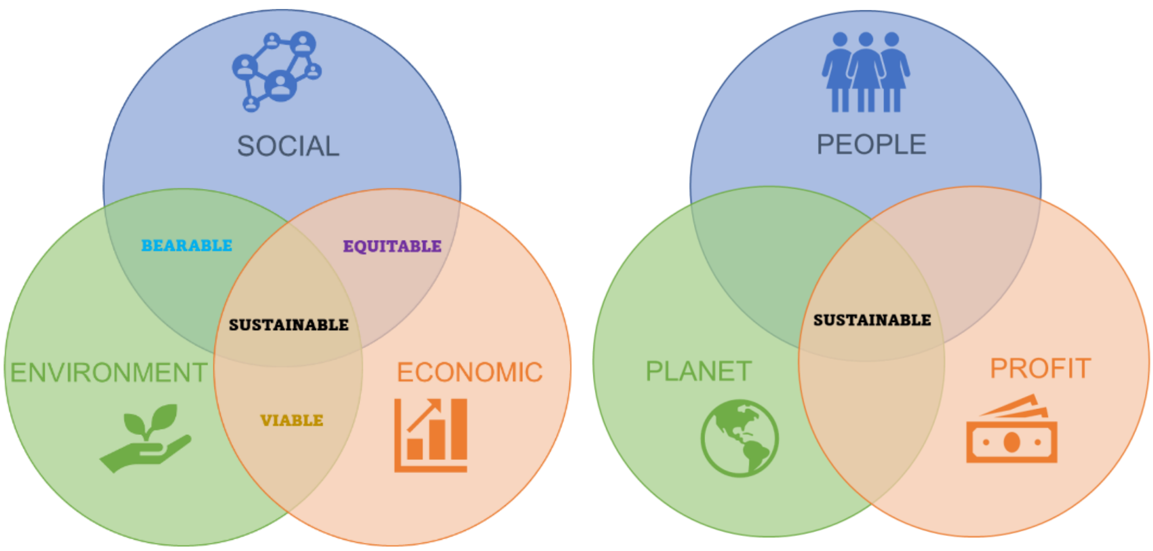

Figure 1.3: Sustainability pillars and "Three P's"

1.1.1 Sustainable Manufacturing

Manufacturing is defined as the transformation of raw materials and information into products for the satisfaction of human needs [14]. Moreover, it is much more than the process through which it is possible to make goods, in fact, it substantially contributes to the world economy and includes different industrial activities from the customer to the factory and vice-versa. It is possible to classify Manufacturing as discrete manufacturing, process industries and services [15]. Discrete manufacturing refers to producing finished products that are distinct items, process manufacturing uses a formula to refine raw ingredients and the final products are undifferentiated, while service manufacturing is not just characterized by tangible products and the customer participates directly in the service process. The manufacturing ecosystem is complex and enables many high-value-added services that create up to two jobs in other sectors for each job in manufacturing [16].

Looking at the international dimension, the EU, the United States and China together accounted for 45 % of both imports and exports of goods globally in 2020, with the EU accounting for around 14% of the world's trade in goods. International trade is an important indicator of a country's economic performance, showing its status on the international stage. The importance of manufacturing is highlighted by the fact that manufactured goods made up 82% of all EU exports and 70% of EU imports, with China and the United States being the main EU trading partners. The United States is the largest destination for EU exports of goods in 2021, while China is the largest origin for EU imports of goods [17].

The importance of manufacturing for both social and economic dimensions in sustainability pillars is irrefutable and can be deduced from the impact it has on the economy and the employment rate of developed countries. The same conclusions can be drawn for the environmental dimension. The manufacturing sector can be considered the second-highest contributor of global greenhouse gases second to the energy sector which includes electricity, gas, steam, and air conditioning supply, which are used by manufacturing companies too [18]. Besides greenhouses gases emissions is also important to consider the impact that manufacturing has on energy consumption (18% of the world's consumption), waste generation of toxic release, floating plastics, product end-of-life and water emission [15].

In this context, the concept of Sustainable Manufacturing emerges. It has become popular since the 1970s to save the environment and has been developed through the years to meet the Sustainability 2030 agenda [19]. Nowadays, this topic is attracting growing attention in the world of scientific research, as can be demonstrated by the growing trend shown in Figure 1.4 reporting the number of published articles per year for "Sustainable Manufacturing" research in the Scopus database.

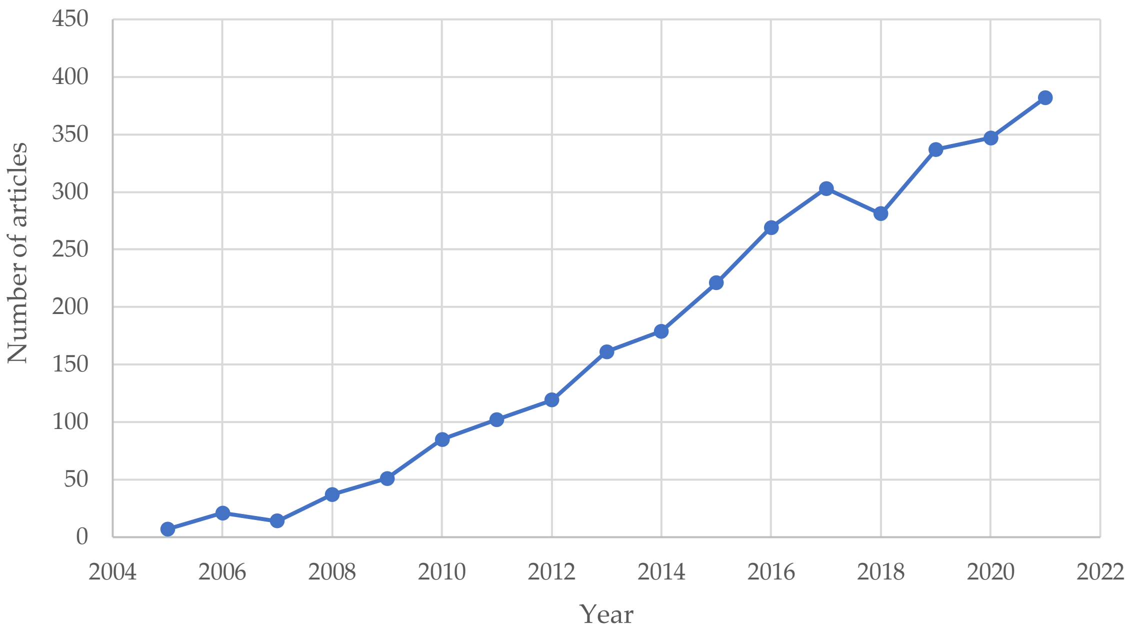

Figure 1.4. Number of published articles per year from "Sustainable Manufacturing" research in the Scopus database

Garetti and Taisch define Sustainable Manufacturing as "the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, can satisfy economical, environmental and social objectives, thus preserving the environment, while continuing to improve the quality of human life." [15] In their framework technology plays the role of enabler together with education which represents a prerequisite for people to address sustainability objectives correctly (Figure 1.5).

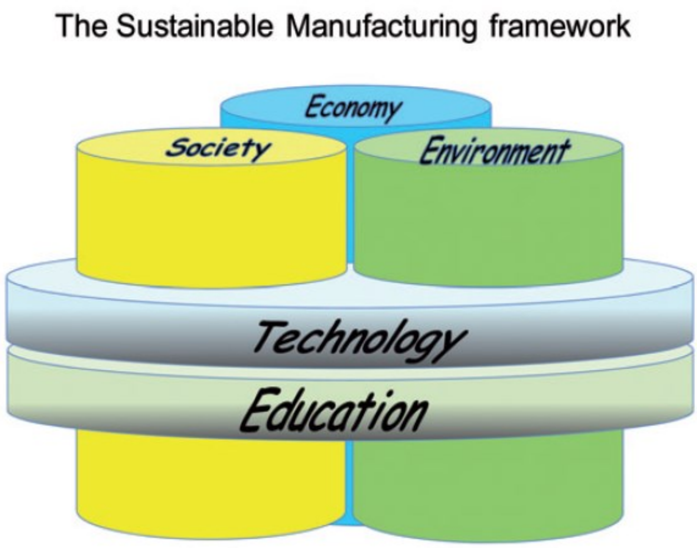

Figure 1.5. Technology and education as sustainability [15]

1.1.2 Drivers toward Sustainable Manufacturing

In the previous section emerges the importance of sustainability thematics for manufacturing. Several reasons are pushing companies to move toward a sustainable transition. Neri A. et al [20] propose a framework of drivers for the adoption of measures in all industrial sustainability areas distinguishing between external and internal drivers. The external drivers are classified into the following categories:

- **Regulatory**; companies have to comply with legislation and governmental regulation [21] and avoid or minimize sanctions and taxes imposed on firms that don't achieve sustainability performance thresholds [22]
- **Support**; it is possible to notice increasing monetary support available in form of external funding from financial institutions [23] together with the creation of public monetary funds for firms [24]. There are also other types of support such as the sharing of knowledge, resources, and common initiatives with other

companies[25], industrial associations or consultants[26], or information and advice coming from the government [27].

- **External pressures;** communities [24], customers, commercial partners, shareholders and public opinion [28] have an increasing awareness regarding sustainability issues. It is also important to consider competitors' actions in sustainability [21].
- **Market;** the prospect of increasing the market share, the new market opportunities [29], the increase in resources price [30] and the related scarcity [28] drive the need for sustainable measures in the industrial sector. Moreover, sustainability can be seen as a concept through which it is possible to build a competitive advantage over competitors [29].

On the other hand, the internal drivers are classified as follows:

- **Organization**; the adoption of sustainability practices can improve the firm brand and image [28]. The firms are willing to improve sustainability-related performance [31] and be compliant with upcoming regulations [32] that can build a competitive edge over those struggling to keep up [33]. Companies aim to have values and culture consistent with sustainability [34] as well as to integrate sustainability principles into the overall firm strategy [35] with a long-term perspective [31].
- **Staff;** the commitment of management and employee to enhance sustainability [34] together with training and education aiming at increasing awareness and knowledge through correct behaviour toward sustainability goals achievement [36].
- **Information;** Through dialogue and encouragement is possible to allow people, tasks, processes and systems to interact purposively and co-operatively to sustainability goals [37]. Availability, trustworthiness, and clarity of information are essential for making properly a decision [23].
- **Innovation;** product [29] and technology innovation [38], together with higher quality [39] and more efficient processes (in terms of resource consumption) [40], can lead firms in improving their sustainability performances.

- **Economic;** The reduction of resource use [24], [41] and accidents [42] can lead to a reduction in cost. Moreover, there is a prospect of increasing income and the maximization of profit serve as an important stimulus [43].

1.1.3 Research trends in Sustainable Manufacturing

[15] propose a framework for the main research clusters in Sustainable Manufacturing classifying the future research directions into 4 categories: enabling technologies, resources and energy management, asset and product life cycle management, and business models and processes as shown in Figure 1.6.

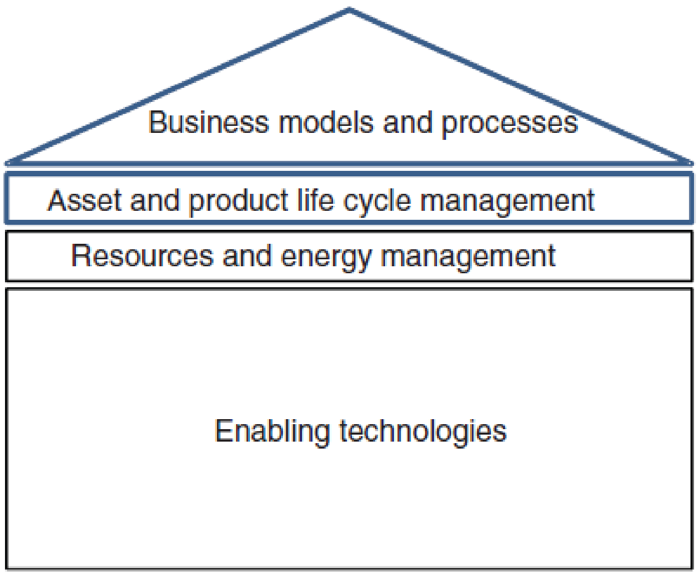

Figure 1.6. Rationale of research clusters in Sustainable Manufacturing [15]

Business models and processes cluster concerns research issues related to new ways to organize sustainable businesses and sustainable supply chains. **Asset and product life cycle management** cluster concerns research issues related to sustainable product design, sustainable life cycle management and maintenance and asset life cycle management. **Resources and energy management** cluster concern research issues related to the reduced use of scarce resources and energy-efficient manufacturing. Scarce resource management and carbon footprint reduction have become important issues, particularly in production planning which represent the focus of this thesis work. **Enabling technologies** cluster concerns the research issues related to new production processes and advanced manufacturing technology and ICTs for manufacturing [15].

[19] propose a different classification, identifying six major research themes in Sustainable Manufacturing where it is evident the key role played by Industry 4.0 in each cluster. It also emerges that the various research themes are strongly interconnected with each other, and it is possible to exploit synergies. The identified clusters are:

- **Sustainable manufacturing process**; machining processes are responsible for a large amount of energy consumption [44] and among the identified research directions, it emerges that there is limited research investigating Industry 4.0 aspects that can help to minimize carbon emissions at a process level.
- **Sustainable planning and scheduling**; those approaches can improve sustainability levels in manufacturing systems, but there are still few studies investigating the opportunities of planning and scheduling in Industry 4.0 [45]. Moreover, only a few sustainability indicators have been used in previous studies [46].
- **Sustainable Manufacturing in Industry 4.0**; Industries can create sustainable value by the usage of Industry 4.0 technologies [47]. Still few studies investigate thematics regarding planning and scheduling, decision making and the role of Industry 4.0 in manufacturing sustainability together with the need to introduce sustainability metrics. In developing countries, the application of those technologies is still lower.
- **Sustainable Manufacturing and Supply Chain**; Industry 4.0 technologies can enhance visibility and improve performances in the supply chain resulting in a need to develop assessment tools to achieve effective and efficient Sustainable Supply Chain Management.

- **Decision-making in Sustainable Manufacturing;** Studies regarding machine learning, artificial intelligence and deep learning remain at a theoretical level resulting in the need to move toward more actual implementations to base the decision-making process on a high volume of data.
- **Sustainable Manufacturing and lean production systems; Lean** tools can help in achieving Sustainable Manufacturing through techniques aiming at reducing waste and consequently environmental issues. The main limitation regards the lack of a measure of the overall impact of environmental management on the performance of the industries.

1.2 Industry 4.0

The concept of "Industrie 4.0" was initially introduced during the Hannover Fair in 2011; In 2013 Germany announced Industry 4.0 as a strategic initiative to take a pioneering role in industries which are currently revolutionising the manufacturing sector [48].

The industry 4.0 Observatory (School of Management of Politecnico di Milano) gives its definition:

> *"Industry 4.0 expresses a vision of the future according to which industrial and manufacturing companies will grow their competitiveness, thanks to digital technologies that allow a higher resource interconnection (plants, people and information), both internal in the factory and distributed along the value chain"*

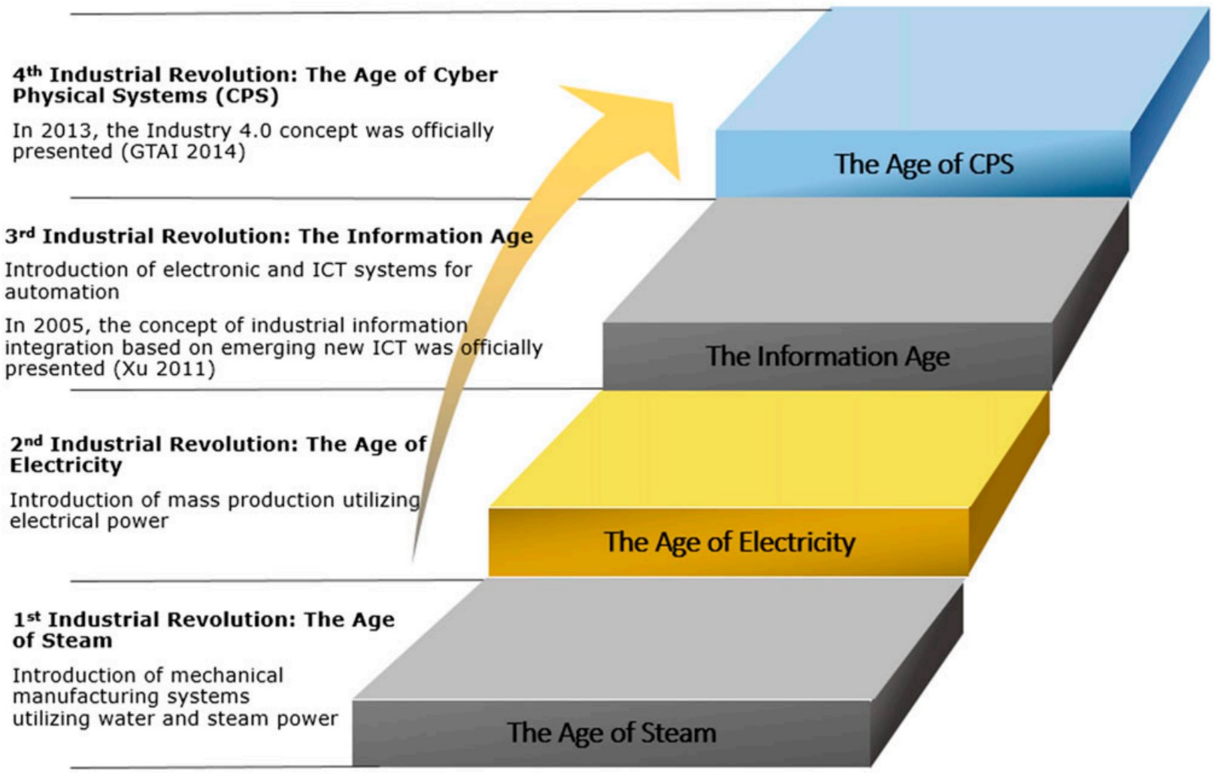

Figure 1.7. The evolution from Industry 1.0 to Industry 4.0 [48]

As highlighted in the previous paragraph, the theme of Industry 4.0 is of particular importance in pursuing the Sustainable Manufacturing agenda. Industry 4.0 and sustainability are considered major trends in the current manufacturing sector. Accordingly to [47], their overlap and synergy may together comprise a distinct industrial wave that will change worldwide production systems forever. This is due to the potential that Industry 4.0 has to fully unlock industrial sustainability through its technology, moving towards a more sustainable society [49]. Among other features, Industry 4.0 promotes autonomous interoperability, agility, flexibility, decision-making, efficiency, and cost reductions [50].

1.2.1 Industry 4.0 technologies

When talking about Industry 4.0 it is impossible not to refer to what are the enabling technologies that support the transition of manufacturing and services toward automated and digitalized processes.

[51] propose a framework for the classification of key enabling technologies for Industry 4.0 based on nine pillars which are shared by several authors in the scientific literature:

- **The Industrial Internet of Things (IIoT)**; represents the connection of two words, “internet” and “things”, so it can be anything like an object or a person connected to the internet at any time and in any place. IoT systems exploit technologies such as RFID, Wireless Sensor Networks, middleware, Cloud Computing, IoT application software and Software Defined Networking. It allows digitalizing all physical systems and through the information retrieved from it, it is possible to adjust production patterns with the use of a virtual copy of the physical world and using sensor data. The Internet of Things (IoT) refers to users-based solutions while when we refer to the Industrial Internet of Things we deal with specific requirements due to the industrial environment that requires real-time data availability and high reliability. Through IIoT systems, it is possible to increase value with additional monitoring and optimization for instance by using Big Data analysis.

- **Cloud Computing (CC)**; is an alternative technology for IT outsourcing resources. CC can lead to advantages in terms of cost reduction thanks to the direct and indirect cost rationalisation on the removal of IT infrastructure. There are different examples of possible deployments of CC in manufacturing industries such as cloud applications, web-based applications, or computer-aided ones. In manufacturing environments, it also emerges the concept of Cloud Manufacturing (CMfg) that is an entirely new type of cloud service that provides manufacturing capabilities. CMfg shifts the manufacturing approach from production-oriented to service-oriented enabling users to request services from all stages of a product lifecycle, ranging from design, manufacturing, management and so on. Figure 1.8 shows a CMfg model.

Figure 1.8. Cloud Manufacturing model [52]

- **Big Data (BD)**; the core characteristic of BD is the data analysis which gives it added value in helping managers in decision-making and/or solving problems related to operations. The characterization of big data is based on ten dimensions that are Volume, Variety, Velocity, Veracity, Vision, Volatility, Verification, Validation, Variability and Value. To explore BD different advanced analytics, methods and tools have been developed such as machine learning and forecasting models. The importance of big data is also evident in the manufacturing sector, where it can help in more rational, informed, and responsive decision-making. BD, IIoT and CC are strongly interrelated with each other. IIoT data are part of BD and BD cannot be explored further without the IIoT. Furthermore, BD is seen as the absorbent application of CC, while CC provides the IT infrastructure of BD
- **Simulation**; is the method that makes use of real models or imagined models. It helps in a better estimation and understanding of the modelled systems or process through its behavioural analysis. Simulation is an indispensable and powerful tool for the implementation of digital manufacturing. Simulation can be a suitable approach when a mathematical model cannot solve uncertain problems with complex systems in the manufacturing industry. It allows experiments for the validation of products, processes or systems design and configuration and helps with cost reduction. Simulation can be used in a wide range of areas as shown in Figure 1.9. It is possible to distinguish two different types of simulation, one for design evaluation and one for operational process performance. The first type can support long-term decisions such as facility layouts, system capacity configurations, material handling systems, flexible manufacturing systems and cellular manufacturing systems, while the second one can help in manufacturing operations planning and scheduling, real-time control, operation policies and maintenance operations. Digital Twin (DT) represent the new simulation modelling paradigm and plays a key role in Industry 4.0. It extends simulation to all product lifecycle phases, combining real-life data with simulation models for better performances based on realistic

data. The usage and the integration of other key technologies of Industry 4.0 are essential for the implementation of the DT.

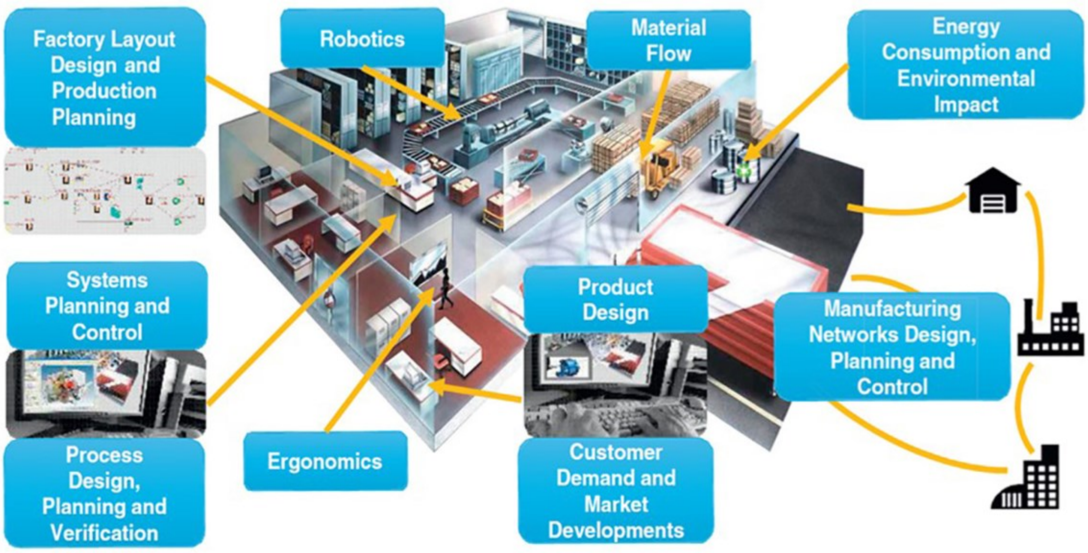

Figure 1.9. Domains on simulation research in manufacturing [53]

- **Augmented Reality (AR)**; has the objective to increase human performance by providing the needed information to complete given tasks. AR can combine real and virtual objects in a real environment and it can run interactively, in 3D, and in real-time. AR finds applications in a wide range of sectors such as entertainment, marketing, tourism, surgery, logistics, manufacturing, maintenance, etc. It can be an efficient technology for manufacturing processes regarding simulation, assistance, and guidance. AR provides dynamic real-time information, so it can suppress most of the paperwork. Maintenance seems to be one of the most promising fields of AR, enhancing human performances in technical maintenance tasks execution and supporting maintenance decision-making.
- **Additive Manufacturing (AM)**; includes a set of technologies that enables "3D printing" of physical objects. AM is an enabling technology helping with new products, new business models, and new supply chains. It is defined as a

process of creating a 3D object based on the deposition of materials layer-by-layer or
drop-by-drop under a computer-controlled system.

- **Horizontal and Vertical Systems Integration**; The connection of engineering, production, marketing, suppliers, and supply chain operations, must create a collaborative scenario of systems integration, according to the information flow and considering the levels of automation. In Industry 4.0 there are two approaches for system integration that are horizontal and vertical. Horizontal integration refers to inter-company integration to establish high-level collaborations by the usage of information systems to enrich the product lifecycle. To achieve horizontal integration, an independent platform based on industrial standards that allow the exchange of data is necessary. Vertical integration refers to intra-company integration and is the foundation for exchanging information and collaboration among the different levels of the enterprise's hierarchy such as corporate planning, production scheduling or management. To achieve vertical integration the digitalization of all the processes within the entire organization is necessary. In literature, it is also proposed another dimension between horizontal and vertical integration that is end-to-end integration which considers the entire product lifecycle linking design, production, and logistics as an example.
- **Autonomous Robots**; these systems are becoming more important together with the shifting of the manufacturing paradigm from mass production toward customized production. Robots with Artificial Intelligence are adaptive and flexible solutions, that can facilitate different product manufacturing, enlarging the product variety, focusing ideally on batch size one. In manufacturing systems, autonomous robots can be very useful in processes such as product development, manufacturing, and assembly phases. They can be helpful in dirty or hazardous industrial applications.
- **Cybersecurity (CS)**; The above technologies such as IoT, virtual environments, remote access, and stored data on cloud systems represent increasing new vulnerabilities leading to potentially compromised information for people and

enterprises. Industry 4.0 creates valuable information and data, and their security is critical for the industry's success. Moreover, manufacturing operations could be shut down by a cyber-attack, causing money loss for the company and potential safety issues for the operators. A cyber-attack can also potentially modify product design, and manipulate process data potentially leading to a loss of trust from customers. For this reason, the need for cybersecurity technologies emerges. Those technologies protect, detect, and respond to attacks.

Another important concept in Industry 4.0 technologies is the Cyber-Physical System (CPS). It facilitates the confluence of physical and virtual spaces, integrating computational and communication processes in interaction with physical processes, and adding new capabilities to physical systems [54]. CPS is a network of interactive input/output physical elements. CPS applied to manufacturing gave rise to Cyber-Physical Production Systems that according to [55] are autonomous and cooperating elements and subsystems interconnected in such a way that, depending on the setting, cover all the stages of the production process, from the shop floor to the logistic networks.

1.3 Production Planning

Planning in manufacturing refers to a wide range of activities spread all over the supply chain from procurement and production to distribution and sales combined with long- to short-term time horizons (Figure 1.10).

Long-term planning is also known as strategic planning and refers to the supply chain structure. Medium-term or tactical planning refers to decisions such as the definition of production targets. Short-term planning, carried out on a daily/weekly basis, aims at determining the assignment of tasks to units and the sequencing of tasks in each unit. When talking about scheduling we are referring to short-term planning at a production level [56].

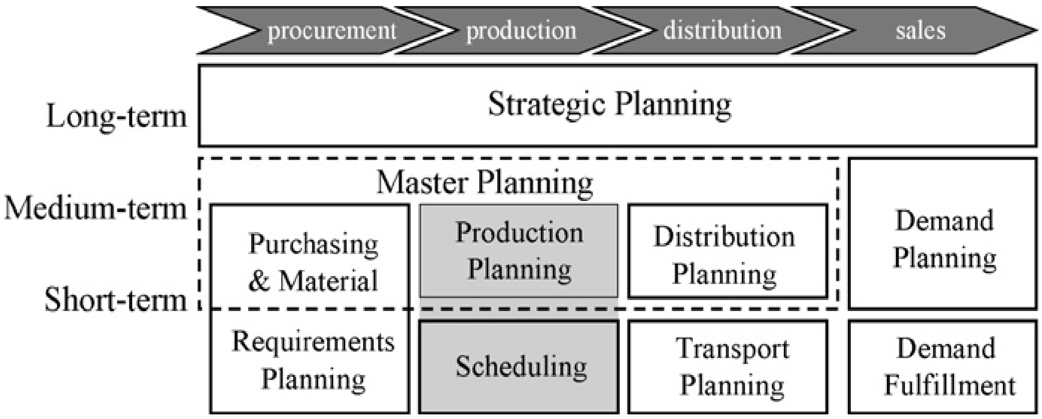

Figure 1.10. Supply chain planning matrix [57]

Production planning plays an important role to pursue sustainability in manufacturing. The previous section about the research trends in Sustainable Manufacturing highlights the importance of production planning in energy-efficient manufacturing, scarce resource management and carbon emission footprint reduction [15]. According to [18] sustainable planning and scheduling is one of the six major research themes in Sustainable Manufacturing. Moreover, still few studies investigate thematics regarding planning and scheduling, the role of Industry 4.0 and the use of appropriate sustainability metrics. Among the different stages of production planning and control, scheduling in Sustainable Manufacturing appears to be the most frequent research subject [46].

1.3.1 Scheduling

This paragraph aims at providing a theoretical background on scheduling. Where not otherwise stated, the information is elaborated from Pinedo's book [58].

Scheduling can be defined as:

> *"a decision-making process that is used on a regular basis in many manufacturing and services industries. It deals with the allocation of resources to tasks over given time periods and its goal is to optimize one or more objectives."*

Scheduling can support decisions for different types of systems such as manufacturing, IT, and logistic. Consequently, the resources and the tasks can take different forms depending on the type of organization. In a manufacturing system, resources are usually machines in a workshop while tasks are operations in a production process. The objectives can also take many different forms depending on what you want to optimize. For instance, a better schedule can result in different benefits for a company such as higher machine utilization, lower production cost, and faster delivery dates.

Scheduling is a difficult problem from two different points of view:

- Technical formulation, difficulties regarding the combinatorial optimization and stochastic modelling,
- Implementation, difficulties depend on the accuracy of the model and the reliability of the input data.

The scheduling function in a production system must interact with many other functions that are substantially different from one situation or another. In general, there is an elaborate information system controlled by a software named Enterprise Resource Planning (ERP) system that plays the role to broadcast information at all organizational levels to support decision-making processes. The scheduling process is not only impacted by the shop floor activities but also by the medium-term to the long-term production planning process for the entire organization. This process aims to optimize the inventory levels, the demand forecast and resource requirements

In a generic manufacturing environment, the information flow can be summarized as reported in Figure 1.11. Orders received are translated into jobs with due dates that are processed by machines in a workcenter in a given order or sequence. Different situations should be taken into account when dealing with scheduling such as busy machines, arrivals of orders with higher priority, machine breakdowns and longer-than-expected processing times. A detailed task schedule helps in maintaining efficiency and control of operations.

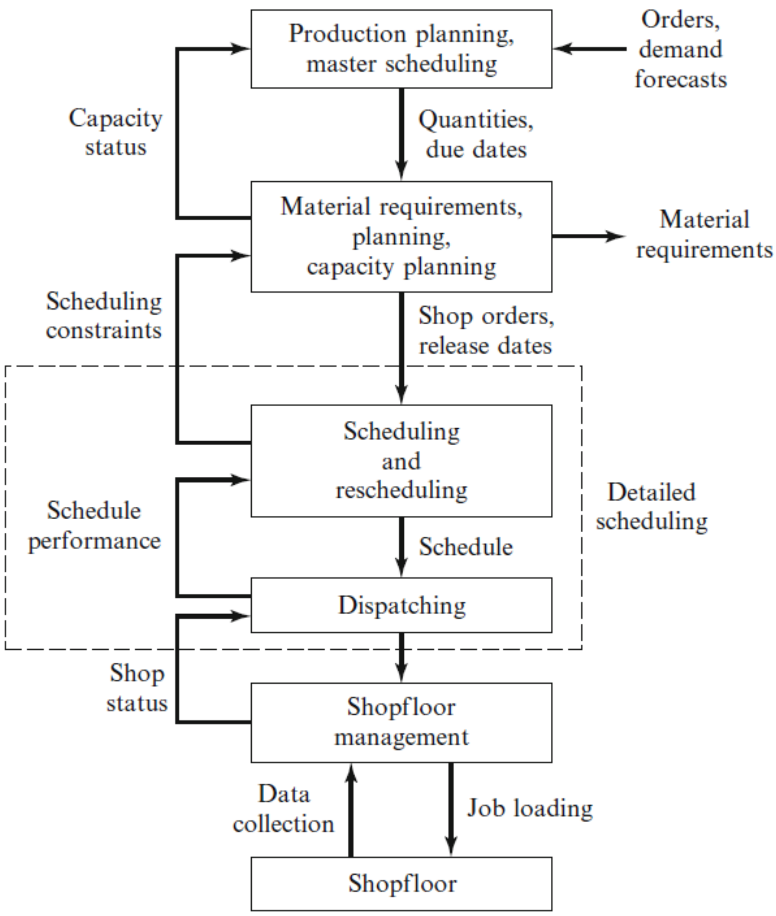

Figure 1.11. Information flow diagram in a manufacturing system [58]

1.3.2 Scheduling Problem definition

A scheduling problem is defined by the **machine environment,** the **details of processing characteristics and constraints,** and the **objective to be minimized**.

The number of jobs and the number of machines is assumed to be finite. One of the most commonly used notations is the following. The number of jobs is denoted by n and the number of machines by m. Usually, the subscript j refers to a job while the subscript i refers to a machine. If a job requires more processing steps or operations, then the pair (i, j) refers to the processing step or operation of job j on machine i.

1.3.2.1 Machine Environment

The possible machine environment in a scheduling problem are:

- **Single Machine**; it is the simplest possible case regarding a single machine configuration and it is a special case of the other more complicated machines environment.
- **Parallel machine**; is a configuration of m machines in parallel and there are different types:
    - Identical machines in parallel; there are m identical machines in parallel and job j requires a single operation and may be processed on any one of the m machines.
    - Machines in parallel with different speeds; also referred to as *uniform machines,* in this machine environment there are m machines in parallel with different speeds and the speeds of the machines are independent of the jobs.
    - Unrelated parallel machines; further generalization of the previous one where there are m machines in parallel with different speeds and the speeds are dependent on the jobs.

- **Flow Shop;** there are *m* machines in series and each job has to be processed on each one of the *m* machines. All the jobs have to follow the same route. Usually, the queue works under the First In First Out (FIFO) discipline. When FIFO logic is applied we refer to a *permutation* flow shop.
    - *Flexible Flow Shop*; this is a generalization of the flow shop and the parallel machine's environment. Instead of m machines in series, there are *c* stages in series with at each stage a number of identical machines in parallel. Flexible flow shops have in the literature at times also been referred to as *hybrid* flow shops and as *multi-processor* flow shops.
- **Job Shop;** each job has its predetermined route to follow. A distinction is made between job shops in which each job visits each machine at most once and job shops in which a job may visit each machine more than once.
    - *Flexible Job Shop*; this is a generalization of the job shop and the parallel machine environments. Instead of *m* machines in series, there are *c* work centers with at each work center a number of identical machines in parallel.
- **Open Shop;** Each job has to be processed on each one of the *m* machines but some of these processing times may be zero. There are no restrictions on the routing of each job through the machine environment.

Many scheduling models that can result from the combinations of the ones listed above are not captured by this framework. For instance, it is possible to define, a more general flexible job shop in which each work center consists of a number of unrelated machines in parallel, as well as it is also possible to define a model that is a mixture of a job shop and an open shop.

1.3.2.2 Details of Processing Characteristics

Different entries can appear as processing restrictions and constraints depending on the process characteristics. It would be impossible to list them all, but here are some of the most common examples to clarify the function of this field. **Release date** specifies that a job j cannot be processed before a specific date; **precedence constraint** specifies the jobs that may have to be completed before another job is allowed to start; **sequence-dependent setup** represents the sequence-dependent setup time that is incurred between the processing of jobs j and k; **job families,** jobs from the same family may have different processing times, but they can be processed on a machine one after another without requiring any setup in between; **batch processing** when a machine may be able to process a number of jobs (a batch) simultaneously, in particular when the batch size is 1 the problem reduces to a conventional scheduling environment; **breakdowns** or machine availability constraints imply that a machine may not be continuously available; **permutation** appear in a flow shop environment with FIFO discipline meaning that the order (or permutation) in which the jobs go through the first machine is maintained throughout the system; **blocking** occurs in a flow shop with limited buffer in between two successive machines when the buffer is full.

Scheduling of jobs that belong to a given (fixed) number of families has received a fair amount of attention in the literature, these types of models have also been referred to as **batch scheduling models.**

1.3.2.3 Objective to be minimized

In a traditional scheduling problem, the objective to be minimized is usually a function of the completion times of the jobs which depend on the schedule. The completion time of the operation of job j on machine i is denoted by C_{ij}. The time job j exits the system (that is, its completion time on the last machine on which it requires processing) is denoted by C_j. The objective may also be a function of the due dates d_j. The lateness (L_j) of a job is defined as the difference between the completion time and the due date and it is positive if the job is completed late or negative if the job is completed early. The tardiness (T_j) of a job is defined as lateness but can't be negative assuming zero as the lowest possible value.

Examples of the possible objective function to be minimized are:

- **Makespan** (C_{max}) is defined as $max(C_1, \dots, C_n)$. It is equivalent to the completion time of the last job to leave the system. A minimum makespan usually implies a good utilization of the machine(s).
- **Maximum Lateness** (L_{max}) is defined as $max(L_1, \dots, L_n)$. It measures the worst violation of the due dates.
- **Total weighted completion time** $(\sum w_j C_j)$ is the sum of the weighted completion times of the n jobs and indicates the total holding or inventory costs incurred by the schedule. The sum of the completion times is in the literature often referred to as the flow time. The total weighted completion time is then referred to as the weighted flow time
- **Total weighted tardiness** $(\sum w_j T_j)$ is a more general cost function than the total weighted completion time.

The objective functions above don't aim to be a complete list as several alternative metrics have been proposed in the literature for evaluating scheduling performances. [59] groups the different scheduling objectives into six broad categories:

1. Job-attributed criteria (e.g., job flow time)
2. Shop-attributed criteria (e.g., machine utilisation)
3. Completion-based criteria (e.g., makespan)
4. Due-date-based criteria (e.g., tardiness)
5. Financial criteria (e.g., job handling cost)
6. Miscellaneous criteria (e.g., labour utilisation).

In scheduling problems, the objective to be optimized may be only one, but it is also probable that the scheduler wants to optimize more than one objective at a time. In the first case, the problem is defined as mono-objective while in the second as multi-objective.

2. Research Methodology

To deeper understand the relationship between sustainability and scheduling, a research methodology has been followed to create a systematic review. The research stages conducted are (1) definition of the research goal and research questions; (2) systematic literature review; (3) development of a methodology to support the integration of new sustainability metrics in scheduling.

2.1 Research Questions definition

In the previous chapter, the increasing attention towards sustainability thematics and their importance for the short-medium term development of modern society has been highlighted. In this context, it emerges that the manufacturing industry plays a major role in contributing to the achievement of the objectives for each of the sustainability pillars, namely economic, social and environmental. Moreover, several drivers are pushing companies to move toward a sustainable transition.

The sustainability paradigm applied to manufacturing systems is defined in the current literature as Sustainable Manufacturing which represents one of the hottest topics in the world of scientific research about engineering. To achieve sustainable production the focus can be placed on the system, the process, and the product, which need the development of improved models, evaluation metrics and optimization methods as tools for realizing sustainability in manufacturing [44]. In production planning, the management of energy and resources together with the reduction of the carbon footprint, have become issues of primary importance. Among all the stages of production planning, scheduling in Sustainable Manufacturing (also defined as **Sustainable Scheduling** or **Green Scheduling**) appears to be the most frequent research subject [46].

Therefore, the research goal is to offer a deeper understanding of the application of sustainability concepts to scheduling purposes and to investigate how the decision-making process at a scheduling level can support the achievement of better sustainability performance in a manufacturing system. In this context the following research questions have been formulated:

RQ1: How a scheduling problem in Sustainable Manufacturing is defined?

RQ2: What are the sustainability metrics currently used in Sustainable Scheduling problems?

RQ3: What are the applications of Industry 4.0 enabling technologies in Sustainable Scheduling?

Consequently, the research aims at providing an overview of the state of the art of scheduling to support Sustainable Manufacturing by evaluating the actual usage of sustainability metrics and industry 4.0 technologies. As previously demonstrated, the selected themes are among the most promising in manufacturing research, thus making it useful to investigate the relationships between them, as suggested by different systematic literature reviews on engineering-related topics.

2.2 Systematic Literature Review

A systematic literature review was conducted to answer the identified research questions. The research has been conducted using the SCOPUS database to identify relevant articles on scheduling in Sustainable Manufacturing. It has been developed according to the following workflow:

- Definition of the keywords to conduct the research
- Definition of research filters based on year and languages
- Definition of exclusion criteria to refine the initial database divided into screening exclusion criteria and eligibility exclusion criteria.
- Screening phase: application of the screening exclusion criteria based on the reading of titles and abstracts
- Eligibility phase: application of the eligibility exclusion criteria based on a deeper reading of the text
- Analysis phase: reading the complete text to search for the necessary information to answer the identified research questions
- Snowballing approach to identify among the citation of the included articles others containing relevant and different information concerning the research questions

The workflow described above is summarized in Figure 2.1.

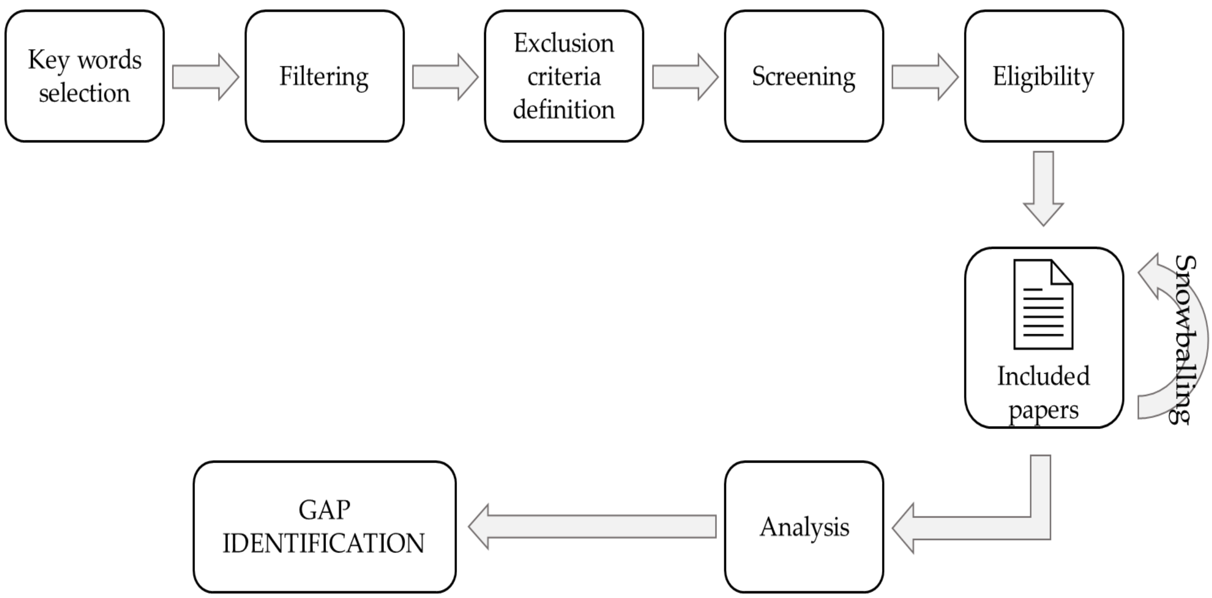

Figure 2.1. Literature Review Process

The next chapter is completely dedicated to the literature review giving a comprehensive understanding of each step of the process and the research output.

2.3 Methodology Development

This sub-chapter is aimed to explain the drivers that led to the development of the proposed methodology for Sustainable Scheduling of manufacturing processes.

Several gaps emerge from the systematic literature review that defines possible future research directions. Among these through the second research question, it emerged that the majority of the Sustainable Scheduling approaches consider energy consumption as the only metric to model the environmental sustainability of the process. Few studies discuss scheduling problems that aim at assessing and optimizing more than a limited number of sustainability metrics. For this reason, a methodology is developed, which details are described in Chapter 4. Its goal is to synthesize the knowledge gained through the literature review into a tool for setting up a scheduling problem that aims at optimizing an overall assessment of the sustainability performance of real manufacturing processes.

3. Literature Review

In Chapter 1 the concepts of Sustainable Manufacturing, Industry 4.0 and Production Scheduling have been introduced. This chapter aims to present an in-depth explanation of the conducted literature review to offer a deeper understanding of the application of sustainability concepts to scheduling purposes. In particular, the general focus is to investigate how the decision-making process at a scheduling level can support the achievement of better sustainability performance in a manufacturing system.

3.1 Sources research and selection

The research has been carried out using the SCOPUS database using the keywords "Sustainable Scheduling" OR "Green Scheduling" searching within the Article title, Abstract, and Keywords. These keywords encompass the typical ways in which the scientific literature refers to a scheduling problem that considers aspects of sustainability. It should be noted that there is a particular scheduling problem called Energy Aware Scheduling which has not been included in the research's keywords. This is because all these types of problems are similar and they don't add much to the defined research goals as they take into account only energy consumption as a sustainability metric. Moreover, many of these articles are included in the research output coming from the defined keywords. In the search, articles from 2006 in English have been set as filters. As a result of the first research, the SCOPUS database gave 164 documents. The trend of the number of publications in Figure 3.1 shows how most of the articles were published starting from 2018, demonstrating the novelty of the theme and the growing attention to it in the last years.

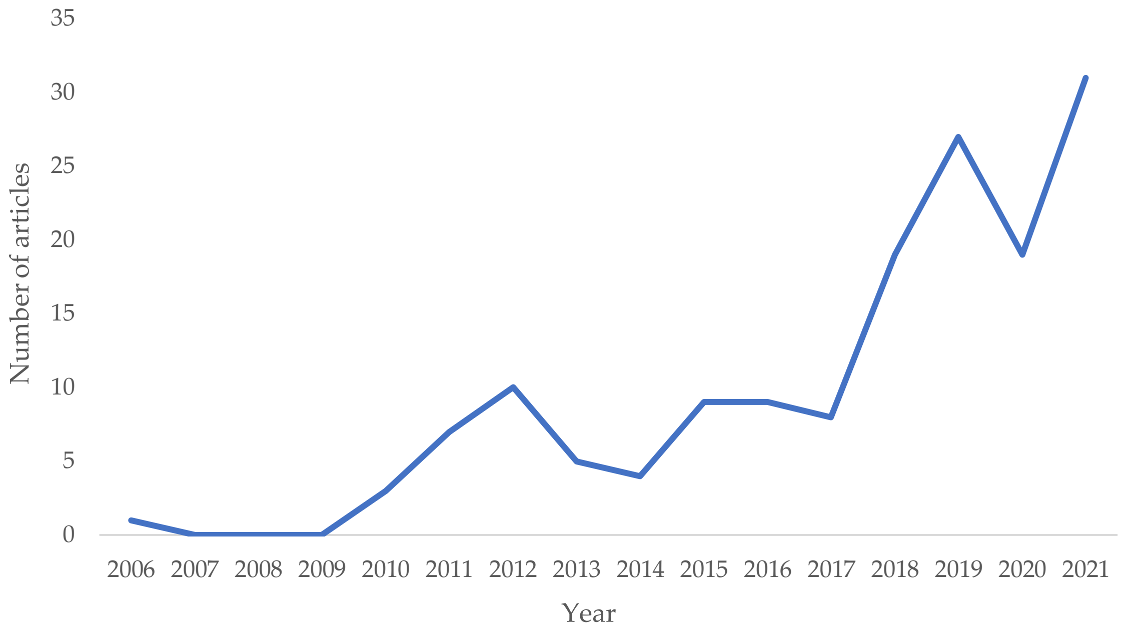

Figure 3.1. Number of Articles published per year

To continue with the selection of the most suitable articles for the purpose of the research the following exclusion criteria have been defined:

- Screening Exclusion Criteria (SEC) based on the reading of titles and abstracts
  - Does the document show a *possible* relationship with both **sustainability** and **production scheduling** in the manufacturing industry?
- Eligibility Exclusion Criteria (EEC) based on a deeper reading of the text
  - Is the full document available for download in English?
  - Does the document show a *clear* relationship with both **sustainability** and **production scheduling** in the manufacturing industry?

86 papers were excluded from the application of the SEC, concerning scheduling problems in other scientific areas such as cloud computing, data centre management peak demand management in utilities and logistics. Other 29 papers were excluded

from the application of the EEC. This resulted in 49 documents to which the 3 papers of the cross-reference snowballing must be added for a total number of 52 papers.

A visual representation of the literature review papers selection process is represented in the flow diagram in Figure 3.2.

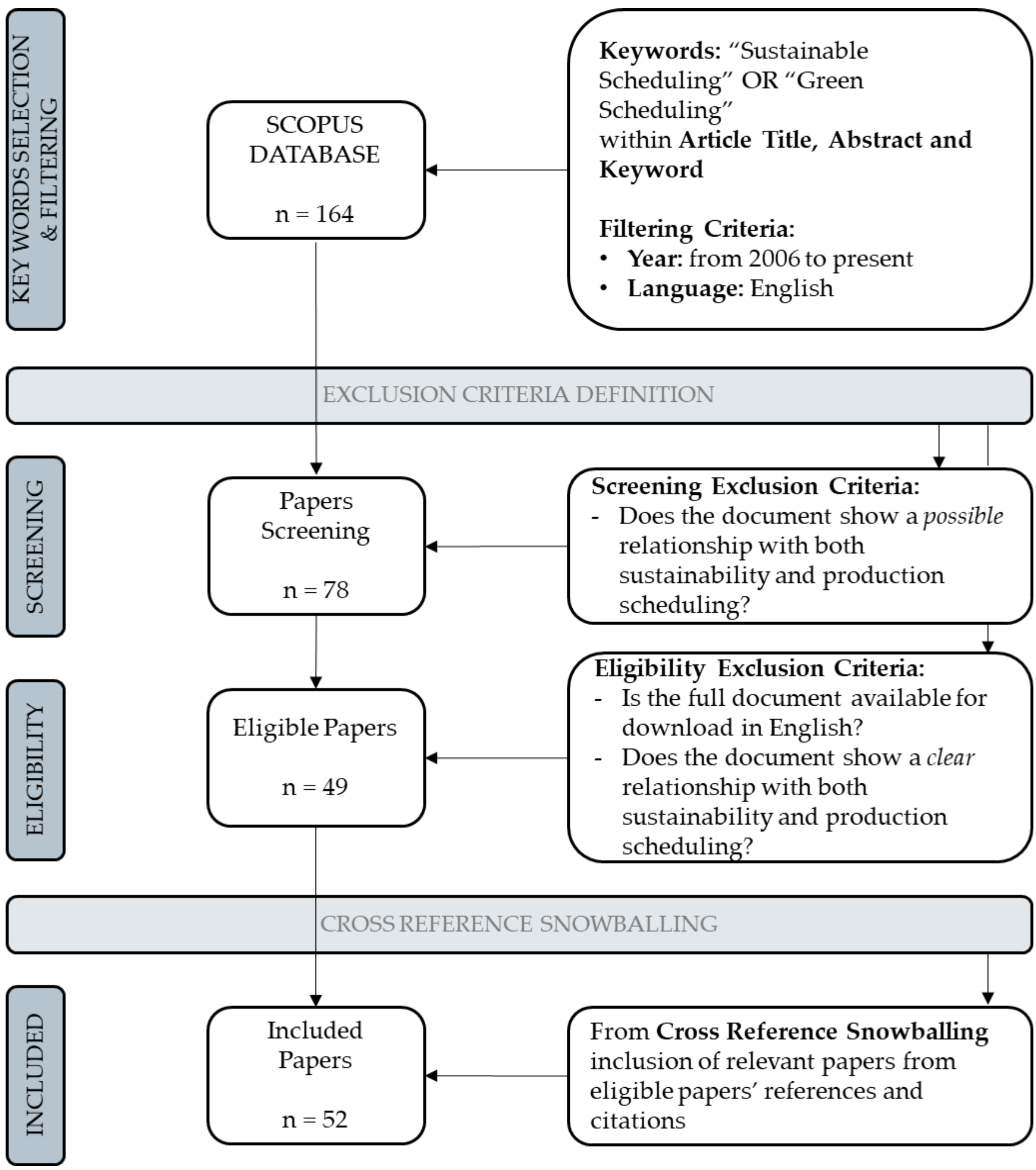

Figure 3.2. Articles Selection Process

3.2 Source Analysis

The search and the selection process resulted in 52 selected papers of which 49 are articles and 3 are conference papers. Those articles and conference papers belong to a variety of sources as shown in Table 3.1. The leading journal is the Journal of Cleaner Production with 11 papers coming from it, while all the others contribute a smaller number of papers, most of them with just one.

In Table 3.1, sources are ranked starting from Q1 (most prestigious) to Q4 (less prestigious). This is done according to the Scimago Journal Rank indicator which gives an objective evaluation of the journal ranking [60]. The information is retrieved from the SCImago Journal & Country Rank which is a publicly available portal that includes the journals and country scientific indicators developed from the information contained in the Scopus database. It is possible to notice that 41 of the 52 articles come from a Q1 source, 10 from a Q2 source and only 1 from a Q3 source. This underlines the authority, prestige, and reliability of the selected articles.

Source	**Number**	**Scimago Journal Rank (SJR)**
Journal of Cleaner Production	11	Q1
Applied Sciences (Switzerland)	3	Q2
European Journal of Operational Research	3	Q1
Swarm and Evolutionary Computation	3	Q1
Sustainability (Switzerland)	2	Q1
Applied Soft Computing	2	Q1
Applied Soft Computing Journal	2	Q1
Computers and Industrial Engineering	2	Q1
IEEE Access	2	Q1
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	2	Q2

Source	Number	Scimago Journal Rank (SJR)
Memetic Computing	2	Q1
Advances in Operations Research	1	Q3
Computers and Chemical Engineering	1	Q1
Computers and Operations Research	1	Q1
Energy	1	Q1
Expert Systems with Applications	1	Q1
IEEE Transactions on Automation Science and Engineering	1	Q1
International Journal of Production Research	1	Q1
International Journal of Sustainable Engineering	1	Q2
International Transactions in Operational Research	1	Q1
Journal of Manufacturing System	1	Q1
Journal of Scheduling	1	Q1
Journal of the Operational Research Society	1	Q1
Mathematical Problems in Engineering	1	Q2
Mathematics	1	Q2
Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture	1	Q1
Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering	1	Q2
Symmetry	1	Q2
Technology in Society	1	Q1

Table 3.1. Ranking of Journals by Number of Publications

3.3 Literature Analysis

In this paragraph, the contents of the selected papers are examined in depth with reference to the formulated research questions. In the end, a research framework is proposed that summarizes the information gathered for each of the included papers.

3.3.1 Research Question 1

The analysis of the bibliographic sources found was first deepened by trying to answer the following research question:

RQ1: How a scheduling problem in Sustainable Manufacturing is defined?

The first research question was formulated to define the traditional characteristics of sustainable scheduling problems. The economic dimension of sustainability can be considered addressed implicitly in the traditional objective of supporting the allocation of resources to tasks in the most efficient way. Sustainable scheduling problems have the objective of integrating the other dimensions of sustainability, that is environmental and/or social, which are dealt with in the second research question.

Table 3.2 shows the characteristics of the scheduling problem of each of the selected papers in terms of machine environment, performance/economic metric used, and if the optimization is mono or multi-objective. The Table contains all 52 selected papers for the literature review sorted from the one with the highest number of citations to the one with the lowest. In the classification reported it is not explicit whether the reported metric is used in the proposed model as an objective function or as a constraint. This is because the present literature review does not aim to deepen the technical issues regarding the difficulties of combinatorial optimization and mathematical modelling in the scheduling problem. Among the selected articles, three are literature reviews which are first analyzed in the following paragraph.

Ref.	Authors	Year	Machine environment	Performance Metrics	Objective
[61]	Shrouf F., et al.	2014	Single Machine	None	Mono
[62]	Gahm C., et al.	2016	**Literature Review**		
[63]	Mansouri S.A., et al.	2016	Flow Shop	Makespan	Multi
[64]	Wu X., et al.	2018	Flexible Job Shop	Makespan	Multi
[46]	Akbar M., et al.	2018	**Literature Review**		
[65]	Lu C., et al.	2019	Hybrid Flow Shop	Makespan	Multi
[66]	Kai Li a,b, et al.	2014	Parallel Machines	Makespan, Total Completion Time	Mono
[67]	Yue D., et al.	2013	Flow Shop	Makespan, Profit	Multi
[68]	Zhou S., et al.	2018	Parallel Machines	Makespan	Multi
[69]	Lu C., et al.	2018	Welding Shop Scheduling Problem	Makespan	Multi
[70]	Jiang E.-D., et al,	2019	Permutation Flow Shop	Makespan	Multi
[71]	Zhang L., et al.	2017	Flexible Job Shop	Makespan	Mono
[72]	Liu Z., et al,	2019	Flexible Job Shop	Makespan	Multi
[73]	Zhang B., et al.	2019	Hybrid Flow Shop	Makespan	Multi
[74]	Han Y., et al.	2020	Flow Shop	Makespan	Multi
[75]	Wang J., et al.	2019	Single Machine & Multi Vehicle routing	None	Mono
[76]	Jiang T., et al.	2019	Job Shop	Completion Time Cost	Multi
[77]	Ròbert Adonyi, et al.	2006	Flow Shop	Makespan	Mono
[78]	Feng Y., et al.	2020	Flexible Workshop	Makespan, Processing cost	Multi
[79]	Lu C., et al.	2021	Flow Shop	Makespan	Multi
[80]	Cota L.P., et al.	2019	Unrelated Parallel Machines	Makespan	Multi
[81]	Safarzadeh H., et al.	2019	Uniform Parallel Machines	Makespan	Multi
[82]	Sai Jishna Pulluru a, et al.	2016	Batch Process Plant	Makespan, Capacity Utilization	Multi
[83]	Zhou B., et al.	2019	Hybrid Flow Shop	Total Weighted Delivery Penalty	Multi
[84]	Cota L.P., et al.	2021	Unrelated Parallel Machines	Makespan	Multi
[85]	Faraji Amiri M., et al.	2020	Flow Shop	Makespan	Multi
[86]	Wu X., et al.	2021	Hybrid Flow Shop	Makespan	Multi
[87]	Xue Y., et al.	2019	Unrelated Parallel Machines	Makespan	Multi
[88]	Tan M., et al.	2019	Unrelated Parallel Machines	Makespan	Mono

Ref.	Authors	Year	Machine environment	Performance Metrics	Objective
[89]	Zandi A., et al.	2020	Parallel Machines	Total Completion Time	Multi
[90]	Assia S., et al.	2020	Flow Shop	Makespan, Service Level	Multi
[91]	Morillo Torres D., et al.	2019	Multi-mode resource-constrained project scheduling problem	Makespan	Multi
[92]	Duan J.-G., et al.	2021	Mixed-line production for large marine power components	Makespan	Multi
[93]	Dong J., et al.	2020	Hybrid Flow Shop	Makespan; Total Prev. Maint. Cost	Multi
[94]	Kong L., et al.	2020	Hybrid Flow Shop	Makespan, Cost	Multi
[95]	Guo H., et al.	2020	Flow Shop	Makespan	Multi
[96]	Zhou B., et al.	2021	Mixed Flow Assembly Line	Line Side Inventory	Multi
[97]	Hidri L., et al.	2021	Parallel Machines	Makespan	Mono
[98]	Afsar S., et al.	2022	Job Shop	Makespan	Multi
[99]	Liu C., et al.	2022	Flexible Job Shop	Makespan, Total Worker cost	Multi
[100]	Prado G.B.V.D., et al.	2021	Flow Shop	Makespan, Profit Margin	Multi
[101]	Zhou B., et al.	2021	Flexible Manufacturing Cells	Makespan	Multi
[102]	Li M., et al.	2021	Flow Shop	Makespan	Multi
[103]	Li Y.-Z., et al.	2021	Permutation Flow Shop	Total Flow Time	Multi
[104]	Nanthapodej R., et al.	2021	Parallel Machines	Makespan	Multi
[105]	Nanthapodej R., et al.	2021	Parallel Machines	Production Overhead Cost (from Makespan)	Multi
[106]	Zuo Y., et al.	2021	Flow Shop	Makespan	Multi
[107]	Bouzid M., et al.	2021	Single Machine	Profit minus Tardiness Penalties	Multi
[108]	Alvarez-Meaza I., et al.	2021	**Literature Review**		
[109]	Yang A., et al.	2019	Single Machine	Completion time (due date constraint)	Mono
[110]	Penn M., et al.	2021	Single Machine	Cost, Profit	Mono
[111]	Zhang H.-L., et al.	2018	Single Machine	Total Flow Time	Multi

Table 3.2. Characteristics of the scheduling problems of the selected articles

3.3.1.1 Existing Literature Reviews

[62] proposes a literature review and a research framework for Energy-efficient scheduling in manufacturing companies, focusing on a sub-category of Sustainable Scheduling in the broader sense. Therefore, the aim of this analysis is about scheduling approaches that lead to increased energy efficiency somewhere in the conversion chain. Energy-efficient scheduling approaches are classified according to the general scheduling characteristics and three specific energy dimensions that are energy coverage, energy supply and energy demand. The authors demonstrate that Energy-efficient scheduling approaches can make a substantial contribution to the more sustainable production of goods.

[46] debates on sustainable scheduling in a broader sense focusing on the presence of different environmental or social factors. A pool of sustainability indicators potentially suitable for sustainable scheduling is identified. Starting from the identified metrics and from the general scheduling characteristics, a research framework, shown in Figure 3.3, is proposed starting from the analysis of 50 scientific articles. This literature review conducted by Akbar M., et al. in 2018, shares the general perspective of the following thesis work, in particular on enlarging the usage of different sustainability metrics in scheduling problems, for which it represents a valuable source used for snowballing and for the critical comparison of results and findings. It is also the only literature review found regarding Sustainable Scheduling from this perspective.

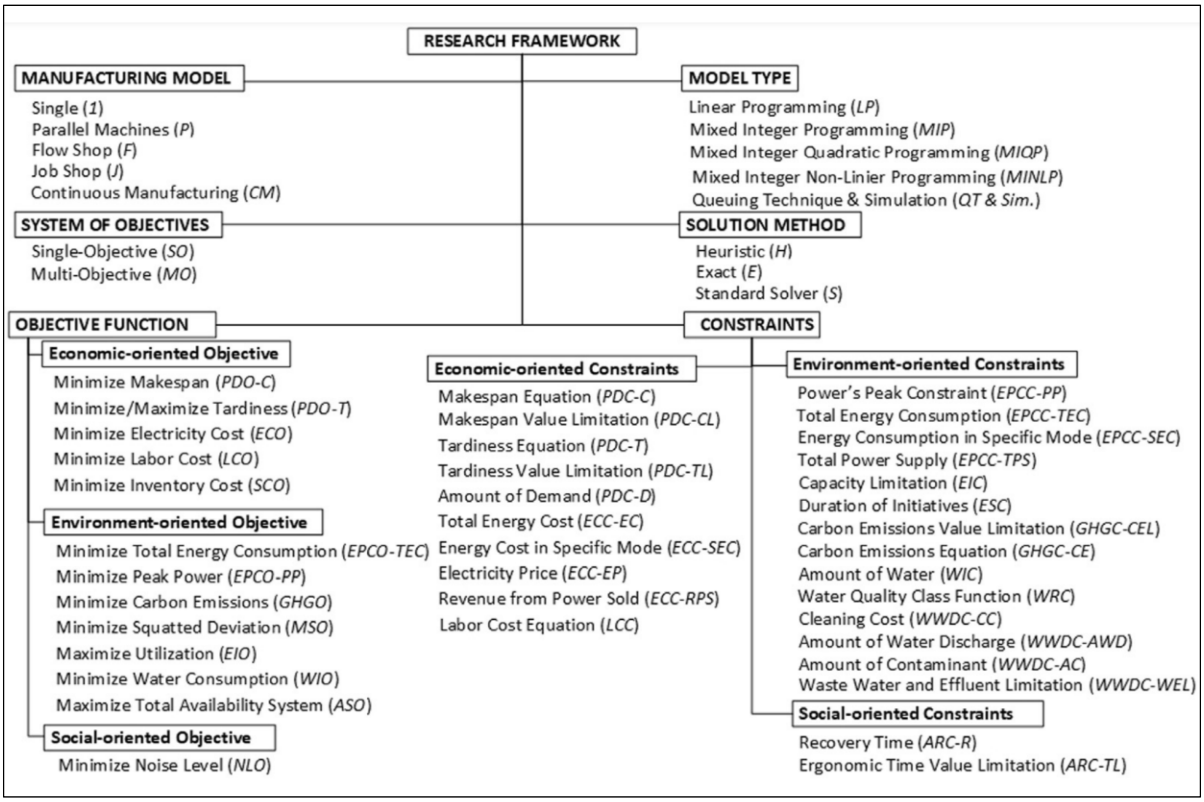

Figure 3.3. Research framework for classification of sustainable scheduling [46]

[108] is based on a bibliometric and network analysis of the scientific research carried out in recent years on Sustainable Scheduling. Bibliometric analysis is defined as a research method, or a research technique, that allows scientific literature to be analyzed and measured quantitatively. Papers not directly related to the manufacturing industry, such as cloud computing, green communication and data centre management, are also considered in this literature review. The used methodology shows the evolution of the Sustainable Scheduling research field and summarizes information regarding when, where, who and about what the academic community is researching in the Sustainable Scheduling field.

From the existing literature reviews emerges that none of the three has investigated the relationship between Industry 4.0 and Sustainable Scheduling. Moreover, the deepening of the aspects of social and environmental sustainability, which do not account only for energy consumption, can be of interest in the context of Sustainable

Scheduling. This supports the reasons for the formulation of the second and third research questions.

3.3.1.2 Machine Environment and Processing Characteristics

The selected articles deal with heterogeneous machine environments, fully covering the classic configurations proposed by Pinedo [58]. The most studied configuration is the Flow Shop, which, considering also its variants, constitutes 36% of the papers. As shown in Figure 3.4, it is followed by Parallel Machines, other configurations not directly attributable to the classic ones, Single Machines and Job Shops.

Problems debating about standard machine environments do not address exactly the same problem, but they are distinguished from each other due to peculiar details of processing characteristics as well as different solution methods used.

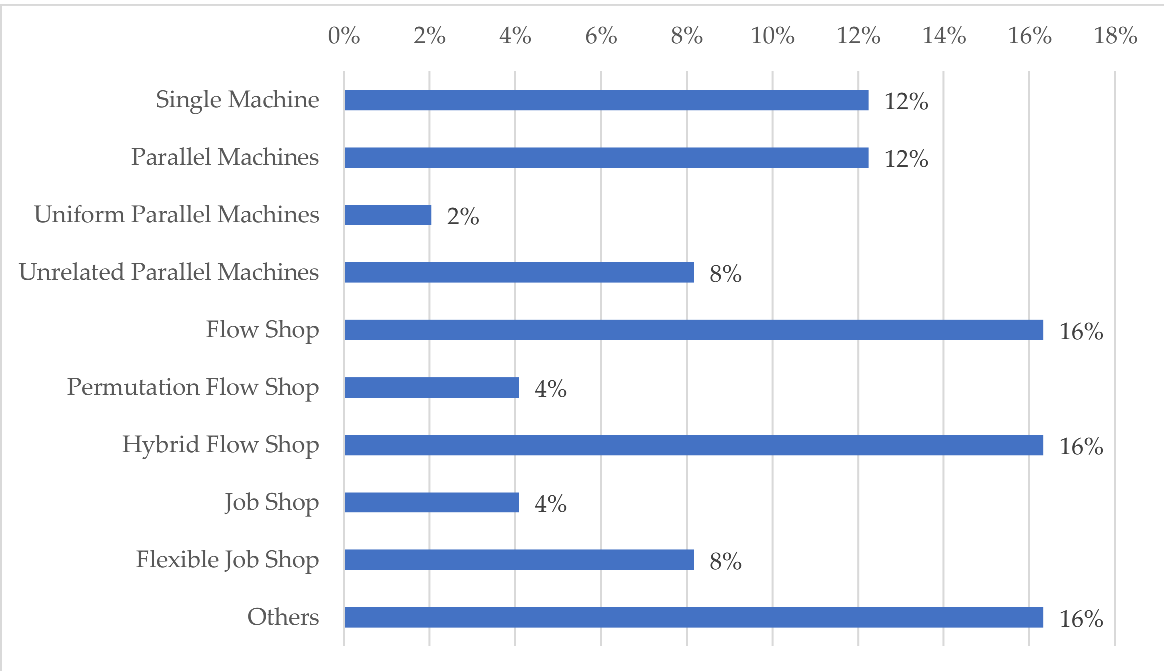

Figure 3.4. Machine environment frequency in selected papers

[75] model a scheduling problem that integrates single-machine scheduling and multi-vehicle routing, while in [109] the authors investigate the single-machine problem with a multi-speed machine. Concerning parallel machines [68], [88] consider batch scheduling while [97] deals with the no-idle constraints where idle time is not permitted between two consecutive processed jobs in any machine. In [84] it is considered the sequence-dependent setup in unrelated parallel machines and so with different machine speeds. [74] model a flow shop scheduling problem taking into account the blocking phenomenon as well as [95] that do the same in ship plane flow line that differs from the traditional flow shop problems because of the characteristics of larger volume and weight that cause the blocking phenomenon. [83] addresses the hybrid flow shop scheduling problem with sequence-dependent setup, while variable speed machine is considered in hybrid flow shop by [73], [102], [106]. The multi-speed machine is investigated also in the job shop scheduling problem addressed by [76] and in the flexible job shop scheduling problem addressed by [64] where the authors also deal with machine on-off decisions that are also considered by [71].

Among the articles that have a machine environment not directly attributable to the more standard and well-known ones in the literature, it is possible to find some that model cases close to real industrial applications. [67] present two different case studies, a multiproduct acrylic fibre batch production process and a multipurpose batch plant with a general network process structure, each one with specific assumptions and model formulations. [69] deals with the welding shop scheduling problem with sequence-dependent setup. This problem has the characteristic that multiple welders can simultaneously process the same operation, increasing the complexity of solving it. [92] addresses a Sustainable Scheduling problem of mixed-line production of large-scale marine power components. [78] considers a flexible workshop with uncertain machine state with real-time monitoring and diagnosis of machine state realized with a hardware system. [101] studies the Flexible Manufacturing Cell problem with material handling robots.

3.3.1.3 Objective and Performance Metric

The vast majority of selected articles, 40 out of 49, address a multi-objective optimization problem. This is also due to the implicit nature of the Sustainable Scheduling problem that combines the optimization of performance with the search for an efficient solution also from the point of view of environmental and social sustainability.

Problems using multi-objective optimization are on average studied more in recent years rather than single-objective ones. Especially in multi-objective optimizations, it is possible to notice how the focus of the study is often to find an efficient solution method since they are in most cases NP-hard (non-deterministic polynomial-time hard) problems. Those are a class of complex problems for which it is not easy to find an optimal solution in a reasonable time, even more, if the objectives to be optimized simultaneously are multiple. However, these problems show great applicability to real-world situations, including scheduling, and the research community is constantly working on techniques and methods to solve these problems [91]. This implies that in the Sustainable Scheduling research field, the main focus is often the development of more efficient algorithms in terms of computational speed and quality of the results obtained. This is confirmed also by [108] which highlights that the different algorithms created for energy optimization in scheduling are the key nodes for its dissemination and the common purpose is to work on the development of new or improved algorithms for green scheduling. According to [91] benchmark libraries are needed to compare and empirically evaluate these algorithms. This aspect of the scheduling problem is not explored in the present thesis, as the algorithmic optimization problem is shared with many other research areas and there is no interest in the development or performance testing of different algorithms.

Regarding mono-objective optimizations in [61], [75] there are no metrics used in the problem formulation for the evaluation of the production efficiency and the optimization regards sustainability metrics. In [71], [109] the performance metric is used as a constraint while the objective remains to optimize the sustainability performance. In [88] different mono-objective optimizations are performed, and the results are compared.

The most used metric for optimizing and/or evaluating the performance of the proposed schedule is the makespan, present in 38 of the 49 papers analyzed. The other metrics are much less frequent and among them, we find other ways of considering process times in the analysis (due date as a constraint, total flow time etc…). Other papers directly translate these performance metrics into related economic metrics such as profit and cost. It is precisely through these metrics that the most traditional scheduling decisions are made, which mainly concern production efficiency and its economical dimension. The traditional formulations inevitably neglect the environmental and social dimensions of sustainability, which in turn include an economic dimension with possible associated costs.

The analyzed Sustainable Scheduling problems, therefore, demonstrate the heterogeneity of machine environments studied through a variety of algorithms and methods that still retains the traditional objective of allocating resources to tasks by optimizing functions related to completion time. The most widely used metric in accomplishing this objective is the makespan. The considerations made so far could also be extended to traditional scheduling problems. Most of these problems use multi-objective optimizations to take into account several aspects of sustainability at the same time. In the next research question, the environmental and social sustainability issues are explored, deepening the characteristic that distinguishes a Sustainable Scheduling problem from a traditional one.

3.3.2 Research Question 2

To further investigate the problems of Sustainable Scheduling from an environmental and social point of view, the following research question has been formulated.

RQ2: What are the sustainability metrics currently used in Sustainable Scheduling problems?

For each selected article, it has been analyzed which metrics are used in addition to those traditionally used in scheduling problems. The result of this analysis is reported in Table 3.3, where not only the metric directly used are flagged but also the metrics necessary to calculate it (e.g., to know the energy cost it is essential to know the energy consumption, for this reason, both are flagged even if the paper focus on the energy cost). Among the metrics identified, most are attributable to the environmental dimension of sustainability i.e., energy consumption, carbon emission, defective products, solid and liquid waste produced, water-related metrics and Life Cycle Assessment for environmental impact. Sometimes these metrics are translated into their economic equivalent i.e., energy cost and taxes on carbon emission. Among the social sustainability, the metrics used are noise pollution and accident rate. The frequency of use of the different metrics is shown in Figure 3.5.

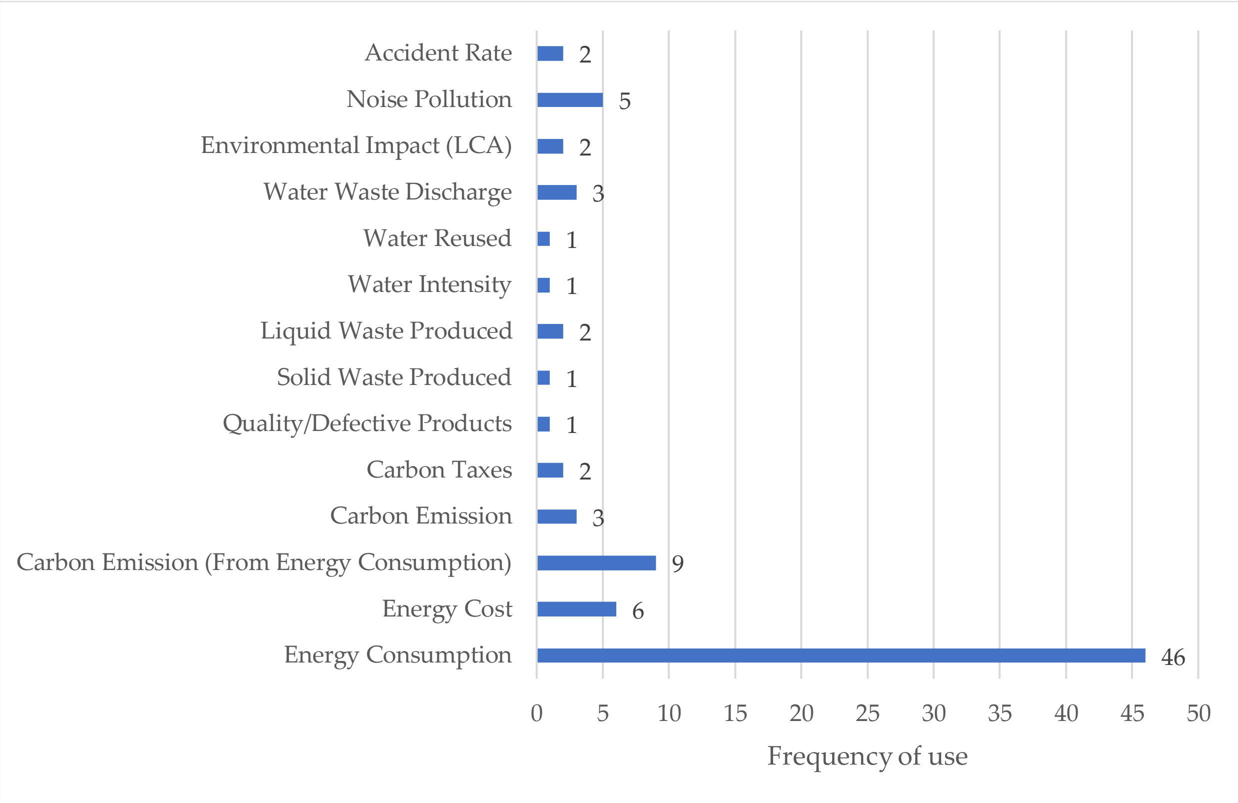

Figure 3.5. Frequency of use of sustainability metrics

	[61] Shrouf F., et al. 2014	[63] Mansouri S.A., et al. 2016	[64] Wu X., et al. 2018	[65] Lu C., et al. 2019	[66] Kai Li a,b, et al. 2014	[67] Yue D., et al. 2013	[68] Zhou S., et al. 2018	[69] Lu C., et al. 2018	[70] Jiang E.-D., et al, 2019	[72] Liu Z., et al, 2019	[71] Zhang L., et al. 2017	[73] Zhang B., et al. 2019	[74] Han Y., et al. 2020	[75] Wang J., et al. 2019	[76] Jiang T., et al. 2019	[77] Robert Adonyi, et al. 2006	[78] Feng Y., et al. 2020	[80] Cota L.P., et al. 2019	[79] Lu C., et al. 2021	[81] Safarzadeh H., et al. 2019	[82] Sai Jishna Pulluru a, et al. 2016	[83] Zhou B., et al. 2019	[84] Cota L.P., et al. 2021	[85] Faraji Amiri M., et al. 2020	[86] Wu X., et al. 2021
Energy Consumption	x	x	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x
Energy Cost	x						x								x					x					
Carbon Emission (From En. Cons.)														x						x					
Carbon Emission																				x					
Carbon Taxes																				x					
Quality/Defective Products																									
Solid Waste Produced																									
Liquid Waste Produced																									
Water Intensity																					x				
Water Reused																					x				
Water Waste Discharge					x											x					x				
Environmental Impact (LCA)						x																			
Noise Pollution				x				x											x						
Safety																			x						

	[87] Xue Y., et al. 2019	[90] Assia S., et al. 2020	[88] Tan M., et al. 2019	[89] Zandi A., et al. 2020	[91] Morillo Torres D., et al. 2019	[93] Dong J., et al. 2020	[92] Duan J.-G., et al. 2021	[95] Guo H., et al. 2020	[94] Kong L., et al. 2020	[96] Zhou B., et al. 2021	[98] Afsar S., et al. 2022	[107] Bouzid M., et al. 2021	[97] Hidri L., et al. 2021	[102] Li M., et al. 2021	[103] Li Y.-Z., et al. 2021	[99] Liu C., et al. 2022	[105] Nanthapodej R., et al. 2021	[104] Nanthapodej R., et al. 2021	[100] Prado G.B.V.D., et al. 2021	[101] Zhou B., et al. 2021	[106] Zuo Y., et al. 2021	[110] Penn M., et al. 2021	[109] Yang A., et al. 2019	[111] Zhang H.-L., et al. 2018
Energy Consumption	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x
Energy Cost			x									x												
Carbon Emission (From En. Cons.)	x					x	x	x				x											x	x
Carbon Emission						x	x																	
Carbon Taxes												x												
Quality/Defective Products																x								
Solid Waste Produced							x																	
Liquid Waste Produced						x	x																	
Water Intensity																								
Water Reused																								
Water Waste Discharge																								
Environmental Impact (LCA)																			x					
Noise Pollution								x								x								
Safety																x								

Table 3.3. Records of sustainability metrics in the selected papers

3.3.2.1 Energy

The papers considering energy consumption are by far the most frequent. In particular, there are only 3 papers where the metrics used are not attributable to energy consumption. Two identified metrics refer directly to energy i.e., *energy consumption* and *energy cost*. Accounting for energy consumption/cost is the most traditional approach to Sustainable Scheduling. In 27 articles energy consumption is the only sustainability metric used, in other 3 it is translated into energy cost while 6 are the cases in which carbon emissions are calculated only taking into account energy consumption. When it is the only parameter of environmental sustainability considered, this type of problem is referred to as Energy Efficient or Energy Aware scheduling problem. Previously it was discussed the literature review and research framework elaborated by [62] on this type of problem, where the ability to reduce energy consumption through decisions at the scheduling level is also demonstrated.

Among the articles analyzed energy consumption or cost optimization can be obtained in different ways. [71] considers machine on-off decision-making that results to be an effective way for energy saving and can be applied easily and conveniently in real production. Machine on-off decision-making is combined with the machine-speed selection by [64] where the non-bottleneck machines are slowed down to reduce energy consumption. It also considers the schedule of production at off-peak to reduce energy costs and pollution. Variable machine speed is also considered by [73], [102], [106]. Time-of-use electricity price that aims at scheduling production during off-peak hours is also investigated by [61], [88], [107].

3.3.2.2 Carbon Emission

9 papers consider *carbon emission* in the formulation of the Sustainable Scheduling problem. However, how total carbon emissions are calculated is not the same for all the papers. In 6 of these, the carbon emissions are computed considering only the energy consumption as a source. This means that the total energy consumption is

simply multiplied by a carbon conversion coefficient to obtain the carbon emission. [107] aims at the maximization of the total profit, i.e., the revenue minus the possible tardiness penalties and the environmental costs. The carbon emissions are computed starting from the energy consumption and are included in the environmental cost formulation by considering a carbon tax proportional to the carbon emissions. In [81] the objective to be minimized is the total green cost. The authors use this metric to model the sustainability effects of the manufacturing resources such as energy consumption (and other natural resources not explicitly defined by the author) or carbon emission. For each machine different green cost rates were assumed. The total green cost depends on the processing time and on the green working cost of each machine, whose formulation is not explicit. [93] proposes a different approach. In addition to considering energy consumption in the calculation of carbon emissions, it also considers lubricant consumption. The authors defined different machine states to model the differences in energy and lubricant consumption. The consumption of lubricant is traced in the present thesis through the usage of a more generic metric i.e., liquid waste produced. [92] adopts the most interesting approach from the point of view of calculating and minimizing the total carbon emissions. The authors formulate a total carbon emission model for the mixed-line production of large marine power components with three carbon emission formulations related to cutting, welding and heat treatment. For each of the foreseen production steps, the total emissions are the sum of those due to energy consumption, and the production of solid and liquid waste. The authors however suggest the possibility to explore more direct and indirect relative carbon emission sources that exist in the production workshop. For example, by removing the hypothesis of the absence of failure, those related to it and the related maintenance activity could be investigated. The analysis shows that there is a trade-off between performance and carbon emissions, which can find a relative optimal point based on the industrial context.

3.3.2.3 Material Wastes

The metrics identified that refer to material wastes are three. *Solid waste produced* and *liquid waste produced* refers to the mass of solid/liquid waste produced for disposal to operate the production process. The third metric refers to wastes due to *quality* issues i.e., *defective rate*. The management of the end-of-life phase of waste is not explored in the analyzed papers. In fact, some of these wastes could be recycled or reused, thus reducing their environmental impact. There are a total of 4 articles that consider material waste. [93] takes into account the consumption of lubricant (liquid waste) in the calculation of the total emissions. [78] introduce the processing quality as one of the optimization objectives, in order to save raw material. The quality is evaluated by the failure rate of products that are considered dependent on the failure rate of machining machines and it is in the end translated into a cost. [99] aims at optimizing a total green index that considers quality through the chip recovery rate. In this formulation the lower the energy consumption and noise value, the better and the higher the chip recovery rate. [92] considers different solid and liquid wastes in the calculation of the total emissions for the different production stages, such as material loss and loss of cutting fluid in the cutting phase, material loss and coolant consumption in the welding phase and cooling medium consumption in heat-treating.

3.3.2.4 Water

Three metrics referring to the consumption and use of water have been identified. These are *water waste discharged* which refers to the volume of wastewater discharged; *water intensity* which refers to the volume of water consumed per unit of product; *water reused* which refers to the total volume of water reused. There are 3 articles in total that use these metrics. [66], [77] look for a solution to minimize cleaning costs and so the water waste discharge. [82] propose an efficient approach for water-integrated scheduling considering all the identified metrics. The results illustrate the tradeoff between production efficiency and water efficiency and show a variety of optimal operation points defined by production schedules. The tradeoffs are analysed to assess the benefit of installing water reuse technology.

3.3.2.5 Social

Two metrics refer to the social sustainability dimension i.e., *noise pollution* and *safety*. There are a total of 5 articles using these metrics. Noise pollution is an important metric for social sustainability since it can lead to health and emotional disorder, for this reason [65], [69], [95] consider noise pollution as an objective to be minimized in the scheduling problem together with energy consumption or carbon emission. [79] uses the negative social criterion that reflects the security and comfort level of the work environment according to factors such as noise pollution and high-risk operation. This criterion is modelled through a penalty coefficient related to the processing time of operation i.e., the longer the processing time, the greater the penalty coefficient. In this paper, the authors consider also the other two aspects of sustainability, the economic one through makespan and the environmental one through energy consumption. [99] define a green index determined by four factors: energy consumption, noise, chip recovery rate, and safety.

3.3.2.6 Environmental Impact (LCA)

Approaches based on Life Cycle Management are attracting increasing attention in the scientific literature with the development of integrative tools and models for this purpose. Among the different approaches, Life Cycle Assessment (LCA) is the most widely used technique in the manufacturing industry [112]. The applications of these approaches to Production Planning and Scheduling are still limited, as confirmed by the only two articles present in this literature review among those selected. [67], [100] apply the Life Cycle Assessment technique based on ISO 14040 with a cradle-to-gate view i.e., an LCA analysis of a product from the extraction phase of raw materials to the exit from the plant. Through this approach, various environmental aspects are considered i.e., waste generation, fugitive emissions, raw material and utility consumptions that are quantified and organized in a Life Cycle Inventory. The information for the different processes and materials is accessible through standard databases. This information converges in the definition of the indicator that is used in the two articles that use the LCA approach i.e., environmental impact. [67] aims at optimizing the environmental impact per functional unit together with the maximization of the ratio between profit and makespan. The concept of a functional unit is important in life cycle analysis, and it avoids that by minimizing just the environmental impact the optimal would lead to zero production. The analysis shows that to obtain greater productivity, a greater environmental impact is necessary. [100] aims at optimizing eco-efficiency and performance efficiency. The performance efficiency is measured through the makespan divided by the normalised environmental impact of each job during the manufacture and the eco-efficiency is based on the economic value proposed in the ISO 14045:2012 guidelines.

3.3.3 Research Question 3

The last research question regards all the scientific areas analyzed in the general research context i.e., Sustainability, Industry 4.0 and Scheduling. These taken individually are of extreme importance, but it has also been noted that the academic world focuses a lot on the relationship these themes can have with each other. As stated by [45] there are still few studies investigating the opportunities of planning and scheduling in Industry 4.0. Moreover, the existing literature reviews that have been analysed, confirm the absence of research regarding Industry 4.0 and Sustainable Scheduling, leading to the formulation of the following research question:

RQ3: What are the applications of Industry 4.0 enabling technologies in Sustainable Scheduling?

To answer this research question, references or application cases of Industry 4.0 technologies were searched in all the 52 selected papers for the systematic literature review. Given the limited results, the search was extended through further searches on the SCOPUS database.

3.3.3.1 Included papers analysis

The use of Information Technology, including computational optimization techniques with the development of intelligent algorithms, can be considered a common aspect of scheduling problems in general (also valid for the selected articles) strictly related to the concept of Industry 4.0. This represents an evident and well-known part of the potential application of Industry 4.0 technologies to scheduling problems, which also applies when the problem extends to more aspects of sustainability. If we extend the analysis to a broader perspective, among the 52 selected articles, 7 articles directly refer to Industry 4.0 in the discussion. These have been analyzed in detail to enlarge the perspective and to define the state-of-the-art of Industry 4.0 in Sustainable Scheduling.

In [78] is debated a hardware system based on IoT (wireless sensor network), edge computing and artificial intelligence (AI) for intelligent monitoring and diagnosis of uncertain machine states. A wireless sensor network (WSN) is established to monitor the key machine indicators according to their characteristics. The authors discuss the importance of cloud computing in the storage and processing of data. But this architecture may not be ideal when real-time decision-making and energy consumption are taken into consideration. Edge computing with embedded AI technologies is an effective solution to address this issue. Edge Computing is an open platform which integrates network, computing, storage and application core capabilities near the object of data source, thus resulting in a shorter device response when compared to cloud computing. It results in a saving in terms of time, energy and cost. The established hardware system has the objective to collect and treat timely and effectively big data in sustainable scheduling. Moreover, the sustainable scheduling system has to react quickly and accurately to the feedback coming from the diagnosis of the machine states corresponding with real-time adjustment called green rescheduling. Thanks to the intelligent monitoring and diagnosis proposed in this paper it is possible to monitor in real-time machine states and to detect promptly faulty machines, no longer relying on the attendance of professional and technical personnel. Therefore, the output of the intelligent monitoring and diagnosis system for machine state is the input to decide whether green rescheduling is necessary or not. The considerations and the method developed have been applied to a virtual simplification of a flexible workshop in a manufacturing enterprise producing auto parts in China. The results obtained justify future development in the application to real industrial cases, despite the costs and computational complexity would be higher. Green rescheduling is also discussed by [107] where machine learning techniques aim at evaluating rescheduling patterns. In this paper, the performances of classical scheduling methods against reinforcement learning techniques are compared and it emerges that the latter can improve the resolution quality and time. [86] debate a system made of robotic cells that is one of the main carriers of the smart manufacturing system. In the robotic cell, the transfer of the job between the machines is performed by the robot. [80] highlight the importance of the sustainable use of energy in the Industry 4.0 revolution. [92] propose as a future issue to be explored the study of the enhanced dynamic workshop scheduling with energy-saving measures based on Digital Twin. [93] aims at constructing more efficient algorithms in the future, combining deep learning and machine learning. According to the authors the concept of Industry 4.0 in manufacturing workshops, combining IoT, cloud computing, and big data technologies can help in building intelligent scheduling algorithms and scheduling rules libraries. According to [102] as smart manufacturing continues to evolve, allowing real-time data from IIoT during manufacturing processes, it is also interesting to study how to process real-time state data for decision-making and optimization of green shop scheduling

From the articles, it emerges that various Industry 4.0 technologies can contribute to the goal of sustainable scheduling. These include cloud computing, edge computing, IoT, big data, robots, and digital twin. These technologies enable real-time data availability, scheduling, and rescheduling. However, their potential is not thoroughly analyzed, and often the use of these technologies is simply proposed as future development.

3.3.3.2 Additional Considerations

Given the few articles available that directly address the topic of Industry 4.0 and Sustainable Scheduling, the search was expanded through citation analysis of the selected articles, and additional Scopus searches. The purpose is to extend the analysis to find additional information and existing literature reviews about the relationship between scheduling and Industry 4.0 with the final aim to understand if some considerations can be extended to sustainability. It may be interesting to point out that a Scopus search among Article Title, Abstract and Keywords for keywords that simultaneously refer to Sustainable/Green Scheduling and Industry 4.0 yields no results. This confirms that despite the importance and potential of the research topic it still does not appear to be properly addressed in the current literature. Instead, there are several studies about scheduling and Industry 4.0 that do not take into account the green/sustainable dimension. Those considered most interesting are discussed below.

[113] introduce the framework for scheduling named Smart Scheduling shown in Figure 3.6. It is a mechanism to mitigate the problems induced by the real-time autonomous behaviour of components of the system by using the tools of Smart Manufacturing and Industry 4.0 environments. The goal of Smart Scheduling is to automatise the solution to the scheduling problems in the integrated frame of Cyber-Physical Production Systems. In the tolerance schedule problems, a range of tolerance is generated to define a level of imperfection in the parameter of the model over which the rescheduling is triggered.

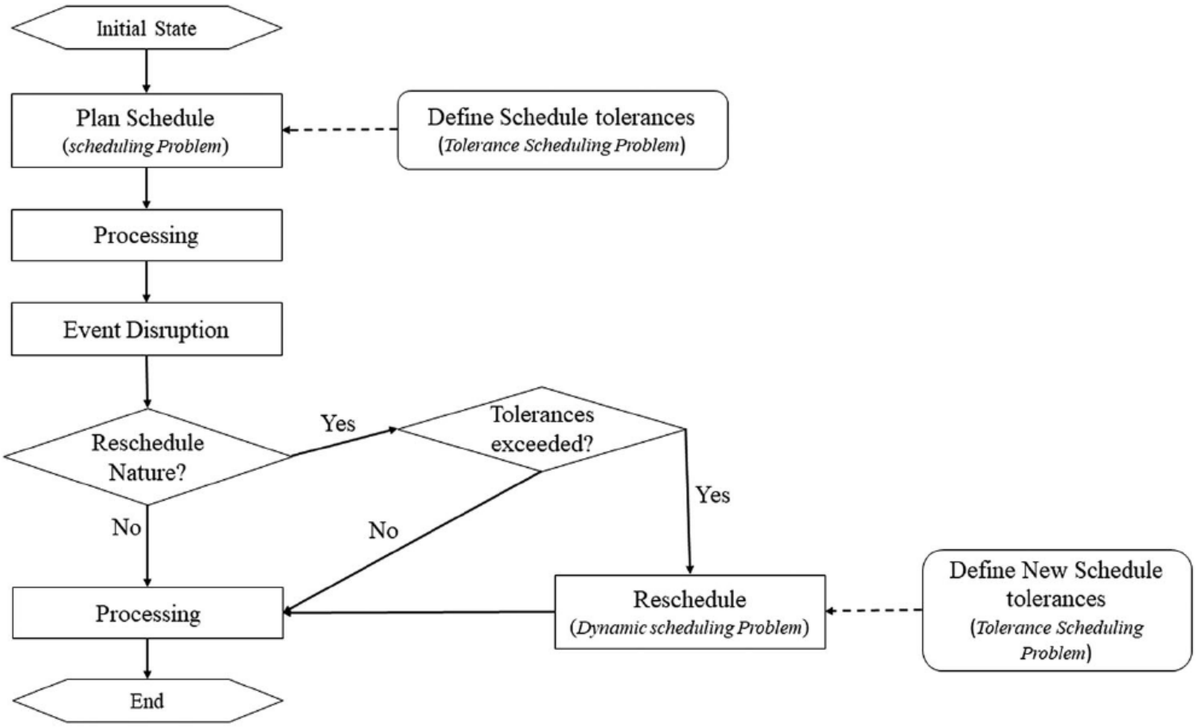

Figure 3.6. Smart Scheduling Schema [113]

According to [114], Industry 4.0 technologies seem to be highly applicable to scheduling objectives. Real-time information could support detailed cost tracking that helps report cost and changes of cost over time and perform more detailed budgeting. It might be interesting to extend these considerations to environmental sustainability performance.

[115] argues that despite scheduling being a classical problem that has been studied for decades in Industry 4.0, a number of new characteristics and requirements exist, which are shown in Figure 3.7. Such architecture stream real-time data that can be useful (such as operating status and energy consumption) to achieve optimal machine scheduling. This situation presents many advantages since machines' breakdown and unavailability can be foreseen, products are smart and can communicate with machines, and each machine is a CPS that can communicate with others in physical and virtual worlds. The characteristics of CPS i.e., autonomous, decentralized and real-time define the complexity of scheduling in Industry 4.0. For a successful implementation, advanced decision-making models and real-time data processing

models are needed. Decision-making models, with appropriate supporting data, could be developed with environmental and social sustainability aspects in mind, by leveraging the advantages these architectures can bring.

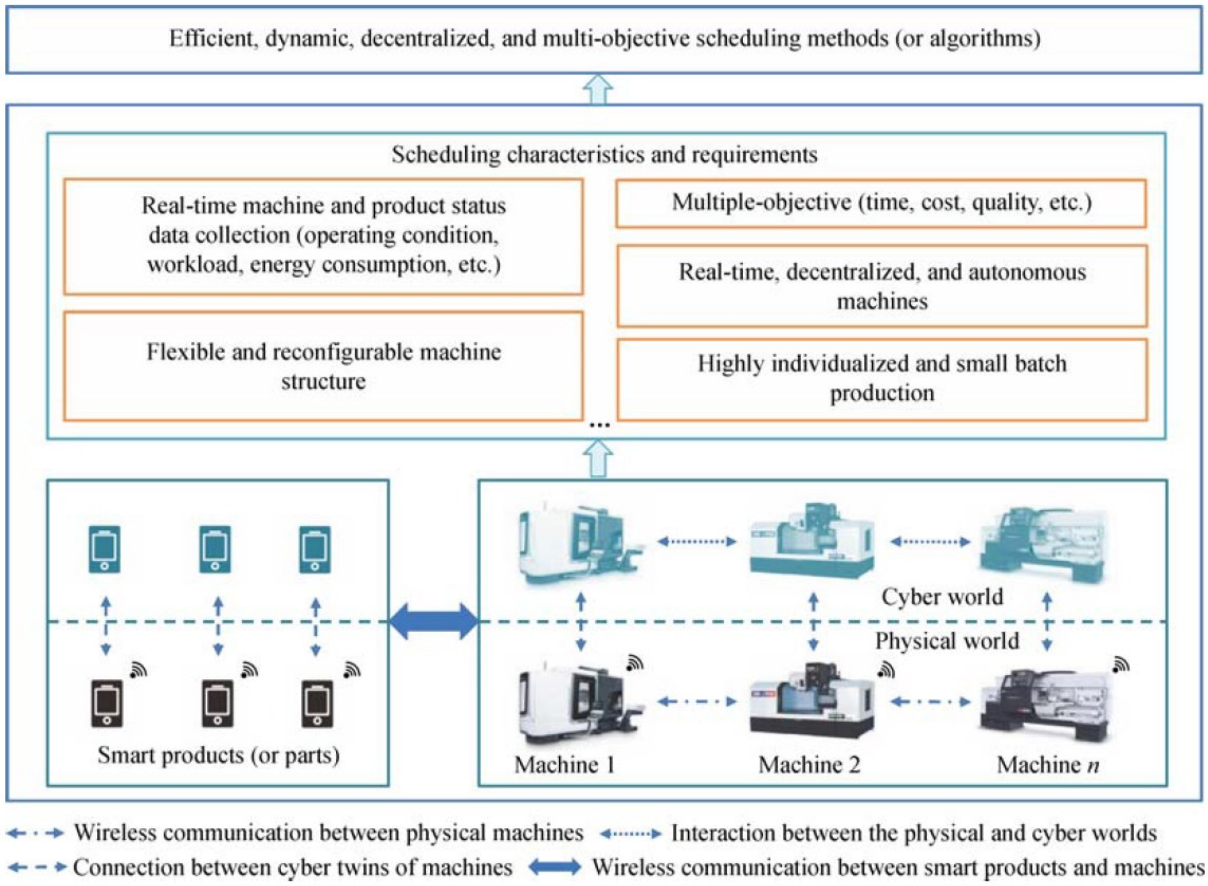

Figure 3.7. Machine scheduling in Industry 4.0 [115]

[116] propose comprehensive research on the applications of Industry 4.0 enabling technologies in manufacturing. Production scheduling and control is the area that received the most attention in the scientific literature. Interestingly, this does not apply when it comes to Sustainable Scheduling, given the small number of articles found in this thesis work. The analysis of [116] shows that all Industry 4.0 technologies are used in production scheduling and control with exception of Blockchain technology.

[52] discuss scheduling in cloud manufacturing (CMfg), which is considered one of the critical means for achieving the aim of CMfg. The authors identify five phases for the scheduling process in cloud manufacturing schematized in Figure 3.8:

- *Order/task submission* from the consumers
- *Preliminary order/task processing* that includes mainly classification, description, analysis, decomposition, and the clarification of functional requirements and non-functional requirements
- *Scheduling* is carried out according to three modules. The core scheduling module aims at generating optimized schedules and managing task execution processes; the scheduling supporting module is responsible for managing scheduling metrics, rules, methods, and algorithms; the service management module manages service-related activities that are necessary for scheduling; the monitoring managing module provides real-time status information necessary for achieving an optimal schedule
- *Result delivery* to the consumer via logistics or the internet
- *Service assessment* to evaluate the overall degree of satisfaction with the results. It is a useful reference for future consumers to select the appropriate service

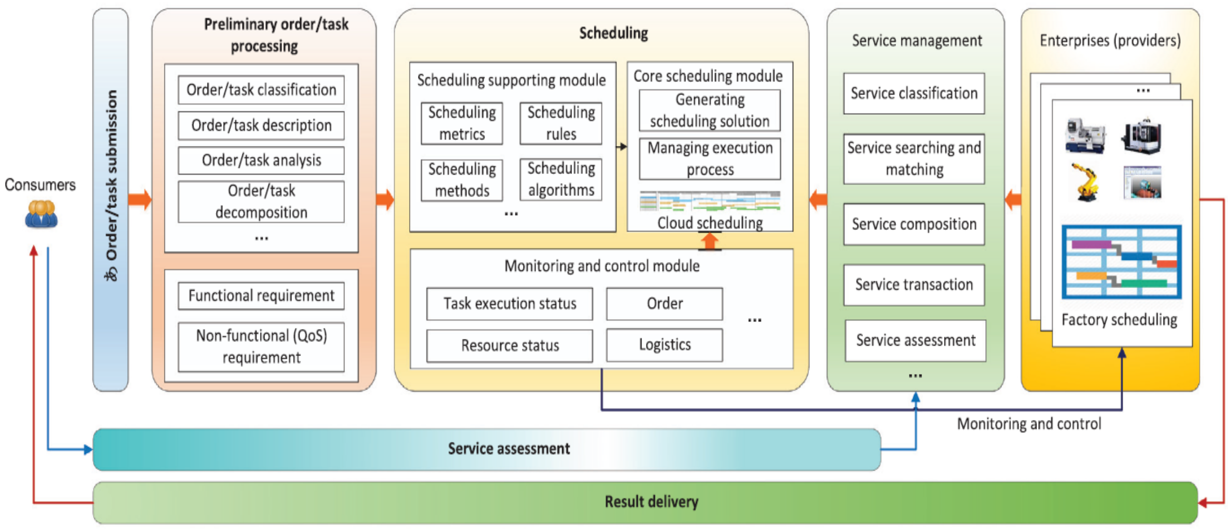

Figure 3.8. Scheduling in CMfg [52]

This research also reviews existing articles in the literature regarding scheduling in cloud manufacturing, classifying each according to the used algorithms, methods and metrics. Only one article uses environmental sustainability metrics according to this classification. It is [117] that considers energy consumption together with cost, priority, reliability and customer satisfaction. On the other hand, several scheduling approaches have been investigated in cloud computing, including many with a sustainability-based approach. Scheduling in cloud computing and cloud manufacturing has many similarities as well as differences. By the way, the research findings on scheduling in cloud computing can be an excellent starting point for extending considerations to cloud manufacturing.

Thus, there are several studies in the literature about scheduling and Industry 4.0, demonstrating the potential these technologies have to improve performance. On the other hand, the topic of environmental and social sustainability still appears to be little addressed, especially in assessing the possible benefits that the proposed models and methodologies can bring.

3.3.4 Research Framework

Table 3.4 shows a classification framework of the articles selected for this systematic literature review, summarizing the most important information gathered in answering the 3 research questions. The objective is to provide an overview of the state of the art as well as to give support for practitioners in the setting of Sustainable Scheduling problems by investigating new characteristics.

In the Table we use the following acronyms in the machine environment field:

- P: Permutation
- H: Hybrid
- F: Flexible

In the Table we refer to environmental sustainability metrics by the following acronyms:

- E: Energy Consumption
- EC: Energy Cost
- C: Carbon Emission
- CE: Carbon Emission from Energy consumption
- CT: Carbon taxes
- Q: Quality/defective rate
- SW: Solid waste produced
- LW: Liquid waste produced
- WI: Water Intensity
- WR: Water Reused
- WD: Water Discharge
- LCA: Environmental Impact (Life cycle assessment methodology

	[61]	[63]	[64]	[65]	[66]	[67]	[68]	[69]	[70]	[71]	[72]	[73]	[74]	[75]	[76]	[77]	[78]	[79]	[80]	[81]	[82]	[83]	[84]	[85]	[86]
Machine Environment																									
Single	x													x											
Parallel					x		x																		
Uniform Parallel																				x					
Unrelate Parallel																			x				x		
Flow Shop		x				x							x			x		x						x	
P-Flow Shop									x																
H-Flow Shop				x								x										x			x
Job Shop															x										
F-Job Shop			x							x	x														
Other								x									x				x				
Objective																									
Mono	x				x					x				x		x									
Multi		x	x	x		x	x	x	x		x	x	x		x		x	x	x	x	x	x	x	x	x
Performance Metric																									
Makespan		x	x	x	x	x	x	x	x	x	x	x	x			x	x	x	x	x	x		x	x	x
Cost															x		x								
Profit						x																			
Other					x																x	x			
Environmental Metric																									
E	x	x	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x
EC	x						x								x					x					
C																				x					
CE														x						x					
CT																				x					
Q																									
SW																									
LW																									
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WR																					x				
WD					x											x					x				
LCA						x																			
Social Metric																									
Noise				x				x										x							
Safety																		x							
Industry 4.0																									
Debated (yes/no)																	x		x						x

	[87]	[88]	[89]	[90]	[91]	[92]	[93]	[94]	[95]	[96]	[97]	[98]	[99]	[100]	[101]	[102]	[103]	[104]	[105]	[106]	[107]	[109]	[110]	[111]
Machine Environment																								
Single																					x	x	x	x
Parallel			x								x							x	x					
Uniform Parallel																								
Unrelate Parallel	x	x																						
Flow Shop				x					x					x		x				x				
P-Flow Shop																	x							
H-Flow Shop							x	x																
Job Shop												x												
F-Job Shop													x											
Other					x	x				x					x									
Objective																								
Mono		x									x											x	x	
Multi	x		x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x			x
Performance Metric																								
Makespan	x	x		x	x	x	x	x	x		x	x	x	x	x	x		x	x	x		x		
Cost							x	x					x						x		x		x	
Profit														x							x		x	
Other			x	x						x							x							x
Environmental Metric																								
E	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x
EC		x																			x			
C						x	x																	
CE	x					x	x		x												x	x		x
CT																					x			
Q													x											
SW						x																		
LW						x	x																	
WI																								
WR																								
WD																								
LCA														x										
Social Metric																								
Noise									x				x											
Safety													x											
Industry 4.0																								
Debated (yes/no)						x	x									x					x			

Table 3.4. Research framework for Sustainable Scheduling

3.4 Gaps Identification

The systematic literature review conducted on Sustainable Scheduling gathers various information that is useful in defining the gaps and possible future research directions. What emerged from the analysis of the different sources with reference to the three research questions formulated is summarized below.

Through the first research question, it has been possible to recognize that there are Sustainable Scheduling problems in the literature covering all standard machine environments with different combinations of details of processing characteristics. In comparison, approaches that discuss real, large-scale manufacturing processes remain limited, and this is something that deserves further investigation in the future to have a realistic assessment of the benefits of the various approaches and methods proposed. The search for computationally efficient and effective algorithms and solution methods is one of the main focuses of scheduling problems, in this regard in addition to the predictable continuous development of optimization methods, it might be necessary to define benchmark methods to compare and empirically evaluate in a standard way these algorithms. It also emerged from some of the analyzed articles the suggestion of removing their model's hypothesis to deepen the proposed problem with an approach closer to real contexts.

The second research question found that there are a limited number of papers that use more than a few environmental or social sustainability metrics simultaneously. On the environmental sustainability dimension, most focus solely on energy consumption. Even approaches based on total carbon emissions often consider energy consumed as the only source of them. On the other hand, the metrics used, albeit individually, are many, demonstrating the possibility of impacting this performance with the scheduling decision-making process. Approaches that consider multiple emission sources or adopt Life Cycle Assessment methodologies to assess total environmental impact are few and recent. It might be interesting to deepen these kinds of approaches given the growing focus on environmental sustainability issues, which among other things could lead to increasingly stringent legislation. This thesis work addresses this objective in the next chapter by developing a methodology that supports the definition of a Sustainable Scheduling problem by selecting all the relevant sustainability metrics to support an all-around optimization and evaluation of environmental sustainability performance. Furthermore, it is useful to investigate the use of new environmental and social sustainability metrics as objectives or constraints in the scheduling problem.

The third research question shows how the applications of Industry 4.0 technologies to Sustainable Scheduling problems are limited. On the other hand, it is shown how Industry 4.0 opens up new possibilities for scheduling, making possible more efficient algorithms, real-time adjustments, increased data availability and accuracy, remote control and process automation. The possible benefits of applying these technologies to improve sustainability performance through scheduling remain to be further investigated.

Figure 3.9 summarizes in clusters the gaps identified and the possible future directions that can be taken in the academic research of sustainable scheduling.

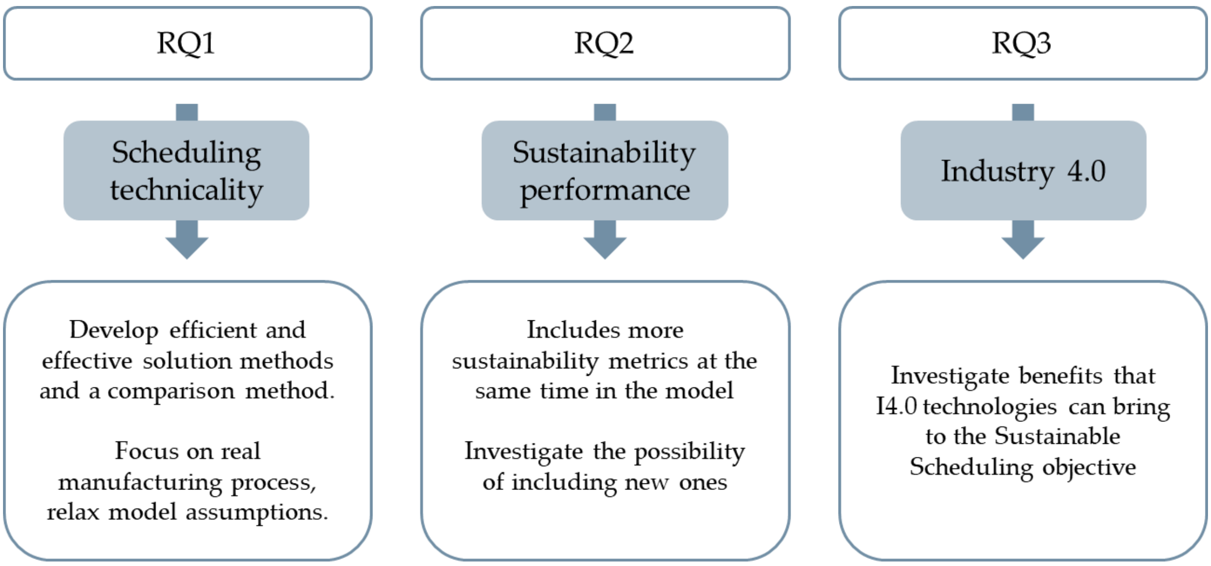

Figure 3.9. Future research suggestions from the literature review

4. Methodology Proposal

According to [118] a methodology is a strategy or architectural design by which the researcher maps out an approach to problem-finding or problem-solving.

This chapter describes the methodology developed. It proposes an approach for the overall assessment of environmental sustainability performance in a Sustainable Scheduling problem for real manufacturing processes. The motivation for the development of this methodology comes from the gaps identified through the second research question.

4.1 Methodology Objectives

The objective of this methodology is to provide a useful tool for setting up a scheduling problem that aims at optimizing an overall assessment of the sustainability performance of manufacturing processes. The methodology is suitable for economic and environmental assessment, aiming to generate greater economic value and produce lower environmental impact. It is intended to be suitable for application in real manufacturing processes by selecting and classifying appropriate environmental sustainability metrics that can be affected by scheduling decisions. This is also achieved by trying to put together what has been learned through the different steps of the systematic literature review presented in the previous chapter.

4.2 Methodology Structure

The proposed methodology consists in 6 steps that guide the setting of the scheduling problem through the inclusion in the scheduling model of a Key Performance Indicator (KPI) for an overall evaluation and optimization of the environmental sustainability of the process. The discussed steps are (i) case study selection and analysis; (ii) definition of the decision variables (iii) definition of the machine states (iv) definition of the sustainability metrics (v) definition of the approach for the environmental assessment (vi) development of the scheduling model.

Figure 4.1 shows a visual representation of the proposed methodology steps, which will be explained in detail in the following sub-chapters.

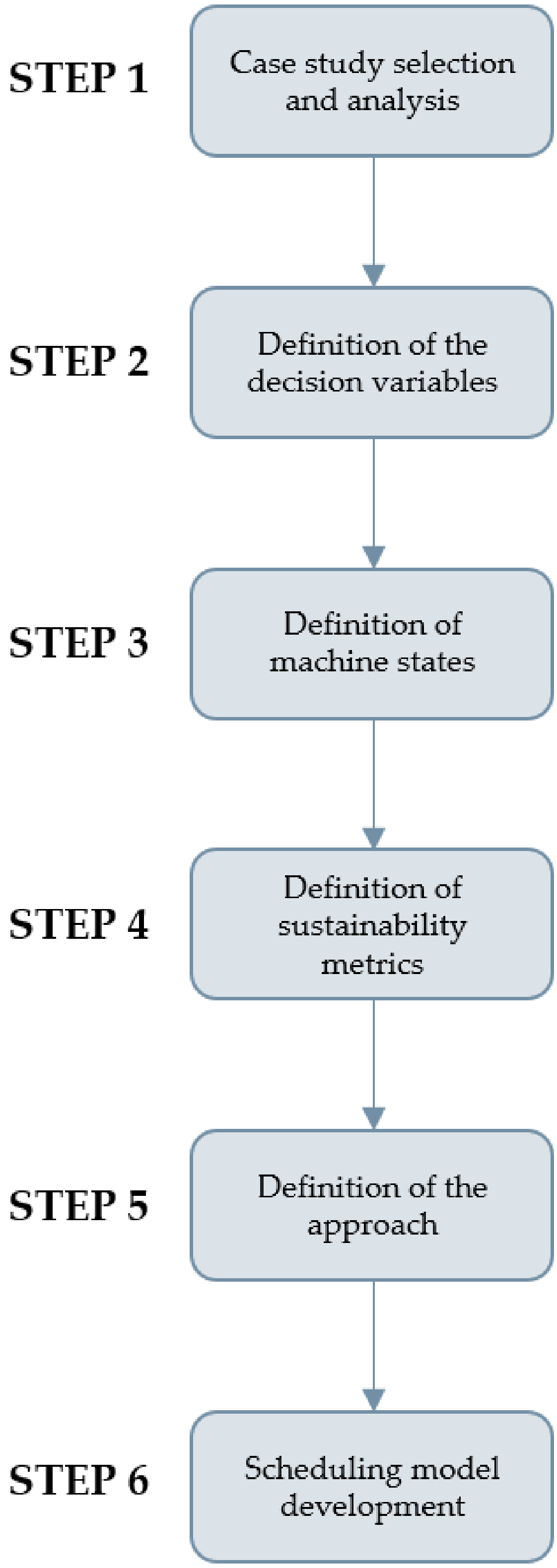

Figure 4.1. Methodology steps

4.2.1 Case Study Selection and Analysis

The first step in the proposed methodology is to select and analyze the characteristics of the manufacturing process of interest. To proceed with the methodology and so define what decision variables, machine states and sustainability metrics we want to include in our scheduling problem, it is indispensable to know the process and its peculiarities. Manufacturing processes have different characteristics depending on the machines involved, the products to be produced, etc. These characteristics have an impact on the scheduling problem, especially when optimisation does not only refer to process times. For this reason at this stage it is necessary to define:

- Total number of machines constituting the process
- Machine environment, i.e., how different machines constitute the process (parallel machines, flow shop, job shop, a combination of standard environment, etc.)
- Types of products to be manufactured and their route in the process
- Characteristics of the different machines constituting the process e.g., type of machine, process times, possible operating conditions, and resources required for proper functioning in each operating condition i.e., machine state
- Details of process characteristics that appear as processing restrictions and constraints depending on the process e.g., precedence constraint, sequence-dependent setup, batch processing, blocking, etc.
- Organization's objectives; to be translated into scheduling objectives, and to guide the decision of the optimum point in the tradeoff between production efficiency and environmental impact.

4.2.2 Decision Variables definition

The objective of the second step of the methodology is the identification of those decision variables that may have an impact on the scheduling optimization problem and on environmental sustainability performance.

According to [119], a decision variable is an unknown in an optimization problem. In other words, those are variables that we can control in a model. As defined precedently starting from the scheduling definition provided by Pinedo in [58], traditional scheduling decisions deal with the allocation of resources to tasks to optimize one or more objectives traditionally related to production efficiency. In a manufacturing process resources are machines while tasks are operations and thus the traditional scheduling decision variable is the allocation of machines to different operations to optimise an objective, e.g., Makespan. We will call this decision a variable *production schedule*. Taking only this decision variable into account is limiting when dealing with Sustainable Scheduling problems. In this case, the optimisation we want to achieve through scheduling is multi-objective and considers environmental sustainability in addition to production efficiency. Therefore, this methodology aims to include in the scheduling model other decision variables that may have an impact on process sustainability performance. Those identified are:

- *Variable machine speed*; variations in machine speed can be modelled through variations in the machine process time. By changing the speed of the machines we obtain higher processing time. But depending on the manufacturing process a higher machine's speed could imply higher energy consumption, higher water consumption, lower quality, increased solid and liquid waste generation lower machine reliability, and vice versa. For example, if we think of a water-cooled machine, it is reasonable to think that working at a lower speed requires less water. This generates a trade-off between production efficiency and environmental impact depending on the characteristics of the manufacturing process.

- *Machine on-off decision*; The decision on whether to turn off a machine may not be obvious. considering the time required for restarting the machine may impact production efficiency. In addition, the energy consumption savings must be sufficient to offset any higher energy consumption in the power-on transient. The machine may require the generation of solid or liquid wastes for restarting or water consumption for cleaning operations. Therefore, even this type of decision can impact both production efficiency and environmental sustainability, depending on the characteristics of the manufacturing process.

Whether these process decisions have an impact on its sustainability performance depends on one's knowledge of the process itself, which is the goal in the first step of the methodology. The magnitude of this impact must be estimated as well. The contribution of Industry 4.0 technologies such as IIoT sensors and Big Data can be crucial for data availability, accurate real-time monitoring of different parameters and the definition of their behaviour as operating conditions change.

4.2.3 Machine States modelling

A finite-state machine is a mathematical model of computation. It is an abstract machine that can be in exactly one of a finite number of states at any given time. State machines can change from one state to another in response to some inputs [120].

During literature reviews, two articles were found that use the modelling of finite-state machines in the Sustainable Scheduling problem [78],[93]. This type of modelling can be useful in scheduling problems, as it allows to model in a more detailed way the behaviour of the machines that constitute the manufacturing process. More detailed modelling also provides a better insight into the behaviour of the machine and its environmental sustainability performance. Depending on the state the machine is in, resource utilisation can vary considerably.

Figure 4.2 shows the possible modelling of a machine in 4 states characterised by different resource consumption.

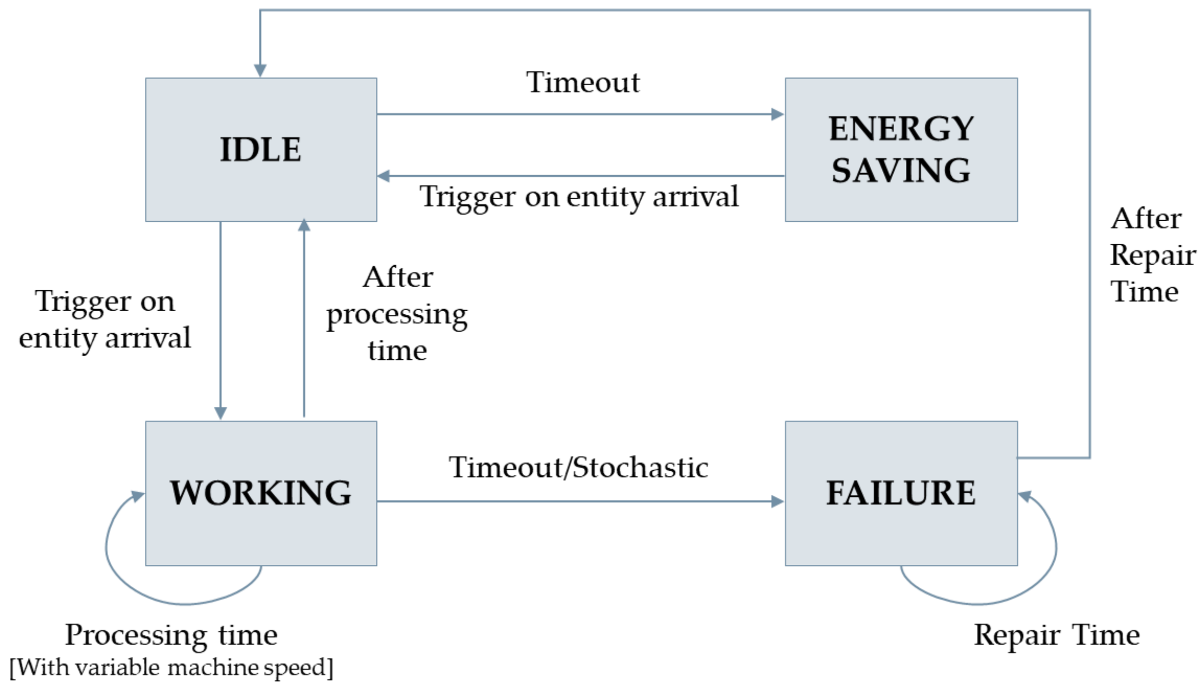

Figure 4.2. Representation of a finite-state machine for Sustainable Scheduling

The proposed modelling is designed with discrete-event simulation in mind, where the trigger for the different states is either the arrival of an entity (representing the arrival of a product to be produced, or more generally an activity for the machine) or the passing of a period of time e.g., timeout. The identified states are:

- *Working State;* this state is triggered by the arrival of an entity, the machine operates for a duration equal to the processing time, and after that time the machine goes into the idle state. It is the state in which higher resource consumption is expected, which also may depend on the selected speed.
- *Idle State;* in this state, the machine is unused and ready to receive an entity to be processed. If a certain time (defined as a timeout) elapses in this state without receiving an entity, the machine goes into energy saving state. Lower resource consumption is expected in this state than in the working state since the machine is not working.
- *Energy Saving State*; the machine goes into this state after a certain period (timeout) has elapsed in the idle state. It is the state in which the lowest resource

consumption is expected because only those processes that are indispensable for the machine's functioning remain active. The arrival of an entity triggers the transition to idle and thus to the working state.

- *Failure State;* this state occurs after a certain time of machine operation (timeout) or stochastically according to the machine's failure probability. In this state, the machine is unavailable to operate and maintenance activities are required to restore its functionality, from which resources (consumables, spare parts...) are consumed.

Depending on the case study, some states might not be necessary or others might be added. Failure state modelling can be improved, but this allows for the consideration that the machine may be not available, removing one of the most frequent assumptions in scheduling models as confirmed by [58]. Moreover, a system based on Industry 4.0 technologies for intelligent monitoring and diagnosis of uncertain machine states can bring benefits to this type of modelling as demonstrated by [78].

4.2.4 Environmental Sustainability Assessment

In order to have an overall assessment of the environmental impact, the different resources required for the operation of the manufacturing process have been organized into 3 categories i.e., energy, waste, and water. The general idea is to define appropriate low-level process metrics for each of the three categories and then aggregate them into a key performance indicator that gives an overall indication of the environmental impact of the process. This metric is intended to be included in the objective function of a Sustainable Scheduling problem. Figure 4.3 shows an outline of the proposed approach for the overall assessment of the sustainability performance of a manufacturing process in scheduling problems. The identified metrics proposed next come from the systematic literature review discussed above.

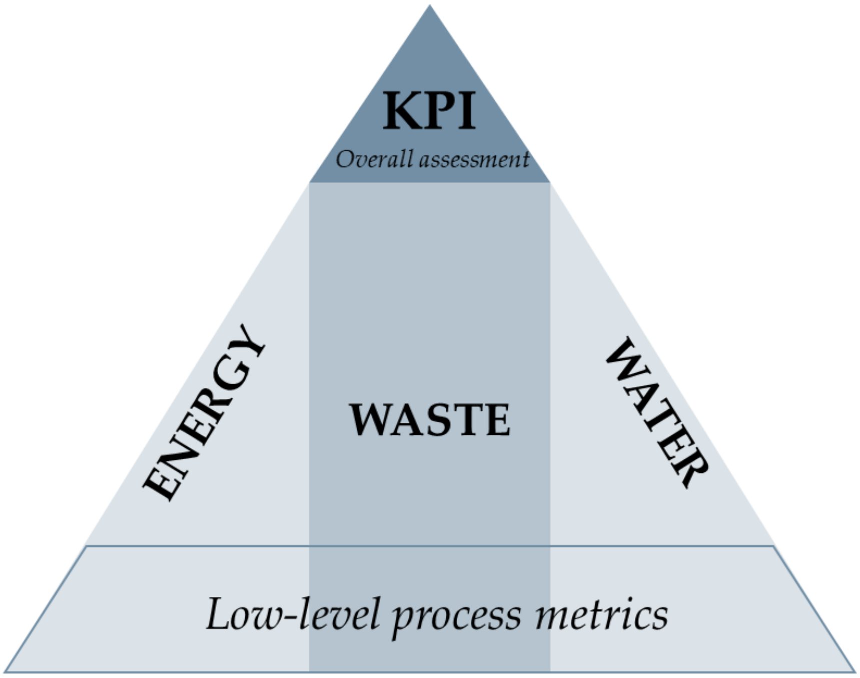

Figure 4.3. Approach to assess overall sustainability performance in scheduling

4.2.4.1 Metrics

The following is a list of possible metrics to include in a Sustainable Scheduling problem. All metrics for environmental sustainability from the previous literature review are included in this methodology, as their applicability to scheduling problems has already been demonstrated. Moreover, these metrics are chosen so that they can be affected by the previously defined decision variables and machine states. Below, the different metrics to measure sustainability performance are categorised and explained in detail. In brackets is the acronym for the metric and its unit of measurement.

The **energy** category includes the following metrics:

- *Energy Consumption (E [kWh]);* is the total amount of energy used by the machine. It may vary according to different machine speeds and different machine states.

- *Percentage of renewable energy (E_{ren} [%]);* it is the percentage of renewable energy produced by the company that is used by the machine. Through this metric, it is also possible to know how much energy is supplied from non-renewable sources. The higher this percentage the lower the importance of energy consumption in environmental impact considerations. In more complex formulations it could be included as a variable with weather conditions, with the timetable, or monitored in real-time.

The **waste** category includes the following metrics:

- *Solid waste produced (SW [kg/min* or *kg]);* is the mass of solid waste produced to operate the machine in different states. It may be dependent on the speed of the machine. In the failure state, might not be time-dependent, but simply dependent on the type of maintenance activity conducted and the related solid materials required. Environmental impact considerations depend on the material of the solid waste produced.
- *Liquid waste produced (LW [kg/min or kg]);* is the mass of liquid waste produced to operate the machine in different states. It may be dependent on the speed of the machine. In the failure state, might not be time-dependent, but simply dependent on the type of maintenance activity conducted and the related liquid materials required. Environmental impact considerations depend on the material of the solid waste produced.
- *Defective Rate (Q [%]);* is the number of defective products in relation to the total produced. Environmental impact considerations depend on the type of product and the materials from which it is made. Through this metric, more in-depth considerations can be made. In fact, depending on the product and the process, part of the material could be recycled, reused, or wasted. With this information, the environmental impact can be considered in more detail.

The **water** category includes the following metrics:

- *Water intensity (WI [m^3/min]);* is the quantity of water required to operate the machine in different states. It may be dependent on the speed of the machine.

- *Percentage of water reused (W_{reu} [%]);* it is the percentage of water reused in the machine operation. Through this metric, it is also possible to know how much water is discharged. The higher this percentage the lower the importance of water intensity in environmental impact considerations.

The metrics discussed require the availability of the relevant data for the manufacturing process under consideration. Industry 4.0 technologies for real-time monitoring can be of great support in this regard, improving the accuracy and responsiveness of the model thanks to available and reliable data.

As previously discussed, the decision variables, machine states, and metrics proposed are strongly interrelated with each other and were defined to consider the environmental sustainability dimension affected by scheduling decisions.

4.2.4.2 Carbon footprint approach

The first approach aims at synthesising environmental sustainability metrics into a single measure based on the carbon footprint concept. It represents the total emissions caused by an organization and is usually expressed as tons of carbon dioxide equivalent (CO_2e) that can be emitted through the burning of fossil fuels, the production and consumption of food, manufactured goods, materials, transportation, and other services [121]. To compute the carbon footprint for each of the proposed metrics, it is, therefore, necessary to define a Conversion Factor (*CF*) in tonnes of carbon dioxide equivalent emissions. Figure 4.4 shows a schematic representation of the following approach.

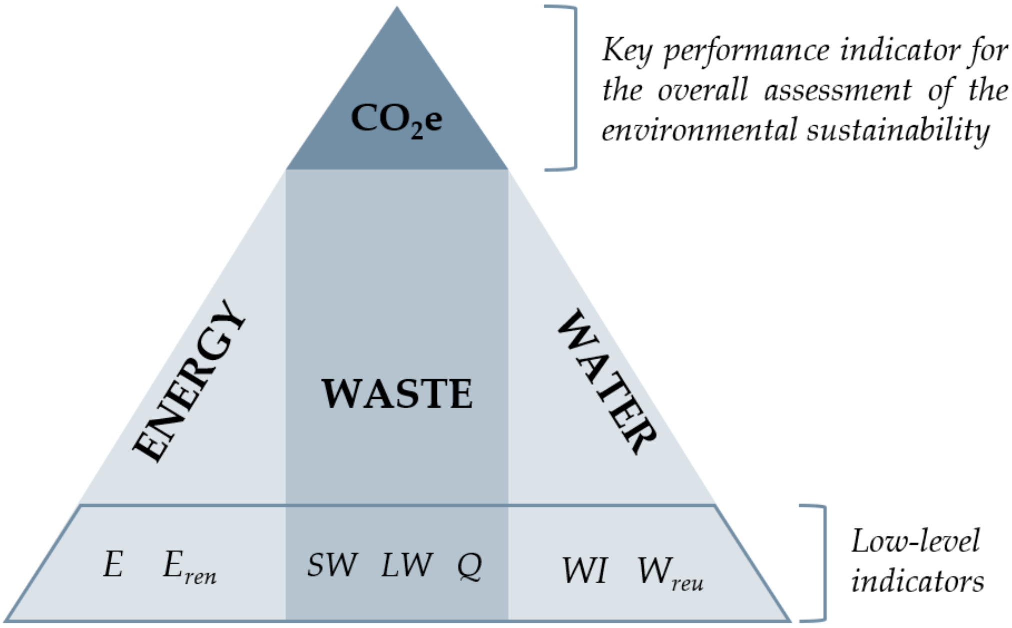

Figure 4.4. CO_2e-based approach for environmental performance assessment

For energy, the *CF* depends on how it has been produced (e.g., petroleum, gas, coal, etc.) Assuming the energy consumed is electricity supplied from the distribution network in Italy, it is possible to assume an average value for the *CF* of 280 CO_2 grams per kWh with updated data up to 2019 retrieved from [122]. The percentage of renewable energy produced by the organisation in question is assumed constant and with a *CF* equal to zero. So, the carbon footprint of energy consumption can be written as:

$$CO_2e_{energy} = CF_{energy} * E * (1 - E_{ren}) \quad (1)$$

For waste, the carbon footprint and *CF* depend on the type of material waste, and it can be expressed in grams of CO_2 per kilogram of material waste. Thus, knowing for each of the *n* material wasted, the quantity of waste produced (*M*) and its *CF*, it is possible to calculate the total carbon footprint for waste as:

$$CO_2e_{waste} = \sum_{k=1}^{n} CF_{waste_k} * M_k \quad (2)$$

For water, the carbon footprint is due to the energy used for water delivery and treatment combined with emissions from the resulting sewage. According to [123] every cubic meter of water consumed generates 10.6 kilograms of CO_2e than could be assumed as *CF*. In the following equation for the calculation of the water carbon footprint, the percentage of water that is reused in the system is assumed to have a zero-carbon footprint.

$$CO_2e_{water} = CF_{water} * WI * (1 - W_{reu}) \tag{3}$$

Therefore, the total carbon dioxide equivalent emissions can be computed as:

$$CO_2e = CO_2e_{energy} + CO_2e_{waste} + CO_2e_{water} \tag{4}$$

The goal of minimising CO_2e through the scheduling optimisation problem results in minimising the overall environmental impact of the manufacturing process under consideration. This approach provides a quantitative estimation of the environmental impact in line with the metrics used internationally for setting environmental sustainability goals.

4.2.4.3 Resource cost approach

The second approach aims at synthesising environmental sustainability metrics into a single measure focused on the economic impact of the different environmental performances. The procedure mirrors that described in the carbon footprint approach. The only difference is that the assessment of sustainability performance is carried out by means of a key performance indicator named Resource Cost (*RC*), obtained from the consumption of resources (i.e., energy, water, waste) multiplied by their unitary cost instead of the carbon conversion factor. Figure 4.5 shows a schematic representation of this approach.

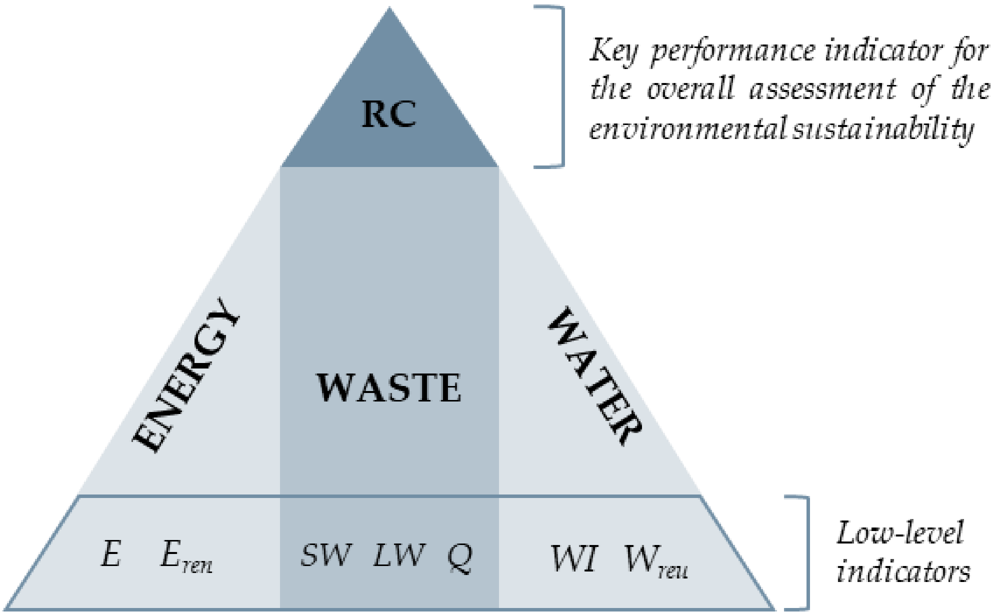

Figure 4.5. Resource Cost-based approach for environmental performance assessment

Such an approach is not very well suited to give an estimation of environmental impact, as the RC calculation is based on the unit costs of different resources. These costs follow market logic, so it is not necessarily true that higher costs imply a higher environmental impact. On the other hand, this type of optimisation would lead to an effective reduction in costs. In certain business contexts, or as a comparison with the carbon footprint approach, a more economic-based approach like this can still be useful.

4.2.4.4 Other approaches

Following the logic of the approaches presented so far, it is possible to develop others that use a different key performance indicator for the overall assessment of environmental sustainability. In fact, instead of using the conversion factor, or the unit cost to aggregate the different low-level indicators, other coefficients can be defined. For example, each organisation, in line with its objectives, or faced with the scarcity of a given resource, may define conversion factors arbitrarily, thus giving the desired importance to different metrics. While such an approach loses out in terms of interpretability of results from an environmental/economic perspective, it may be more functional to the achievement of the organization's goals.

4.2.5 Scheduling Model

As the final step, the metric defined for the overall evaluation has to be included in the scheduling model. The problem formulation can be multi-objective so that the proposed optimisation evaluates both the performance of the process (e.g., through makespan) and an overall assessment of the environmental performances obtained from the approaches described above. Through this formulation is possible to evaluate the tradeoff in the set of all Pareto-efficient solutions and select the one desired by the organisation, consistent with its objectives. The development of the model type and the solution method is not investigated in this thesis since it does not focus on combinatorial optimization and mathematical modelling of the scheduling problem. However, at this point is necessary to proceed with the choice and definition of how to model the scheduling problem (linear programming, mixed integer programming, simulation, etc.) and which algorithmic solution method to use.

This methodology is designed to be applicable in real industrial contexts. According to [58] real-world scheduling problems are very different from the mathematical model studied by researchers, but they provide useful insights into many scheduling problems for the development of the algorithmic framework for a large number of real-world scheduling systems. This methodology is developed precisely by synthesising and processing what has emerged from the different approaches found in the literature. Therefore, the articles analysed in the literature review and classified in the research framework offer a valuable source for the progressive, challenging development of sustainable scheduling mathematical models and solution methods for the real industrial context by following this methodology.

5. Conclusion and Future Development

5.1 Conclusion

The path towards the sustainable development of society in the short to medium term cannot fail to consider the importance of the manufacturing sector for each of the three pillars of sustainability. This research focused on a Sustainable Manufacturing research cluster widely shared by the scientific community i.e., production scheduling. In particular, the goal was to define how scheduling can contribute to the transition to more sustainable manufacturing processes. This was done by first analysing the state of the art of Sustainable Scheduling through a systematic literature review, defining its characteristics and grouping them into a research framework to support practitioners in the setting of Sustainable Scheduling problems that aims at investigating new characteristics.

From the systematic literature analysis and through the formulated research questions, possible future research directions on Sustainable Scheduling. Among them, it emerged that there are few studies that discuss scheduling problems that aim at assessing and optimising the total environmental impact. The objective of this methodology is to provide a useful tool for setting up a scheduling problem that aims at optimizing an overall assessment of the sustainability performance of manufacturing processes. The main contributions of the presented methodology are:

- It is designed to be applied to real manufacturing processes and to capture differences and peculiarities in terms of environmental sustainability
- It defines decision variables and machine states that are differential in terms of sustainability performance optimization.
- It comprehensively summarises the approaches and the methods emerging from the systematic literature review.
- It proposes a flexible approach for the assessment of environmental sustainability performance, including all metrics that have been used in the papers analysed during the literature review.
- It provides a method to aggregate the selected metrics into a single high-level indicator that can be defined according to the organisation's objectives and then included in the objective function of the scheduling problem.

The main limitations of the developed methodology are:

- It neglects the social dimension of sustainability.
- It requires data that may not be easily available.
- It implies additional difficulties in the mathematical modelling and in the combinatorial optimization of the problem.

Inclusive optimisation of the overall environmental sustainability performance of the manufacturing process through scheduling can be particularly interesting also in the case of possible sanctions and taxes imposed on firms that don't achieve sustainability performance thresholds coming from more restrictive legislation. Optimisation of this kind can also be important due to customers' increasing awareness regarding sustainability issues and the increase in resource price and related scarcity that we are facing in the last few years. Since scheduling is an organisational measure, such an approach makes an almost cost-free contribution towards greater sustainability of production processes.

5.2 Future development

The main future development of the proposed methodology is its practical application through the formulation of a sustainable scheduling model accordingly to what has been proposed and defined by the different methodology's steps. One possibility would be to investigate the potential of discrete-event simulation to model such a problem.

The proposed methodology is suitable for economic and environmental assessment, it could be extended by integrating the social sustainability dimension. It is possible to extend the methodology in each of the proposed individual steps, investigating the possible use of other decision variables, machine states, metrics, and approaches for the overall assessment of sustainability performance consistent with the selected manufacturing process characteristics.

Through Industry 4.0 technologies, data availability can be ensured. From the implementation of these technologies, real-time process monitoring, and subsequent optimization can be achieved. It would be interesting to investigate how these technologies and the possible replication of the industrial process in a virtual environment (i.e. digital twin) can contribute to Sustainable Scheduling.

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