Sustainability 4.0

Assessing the triple bottom line in a smart manufacturing context

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Thesis to obtain the Master of Science Degree in

Industrial Engineering and Management

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July 2019

“(…)

Sou um técnico, mas tenho técnica só dentro da técnica.

Fora disso sou doido, com todo o direito a sê-lo.

Com todo o direito a sê-lo, ouviram?

(…)”

Álvaro de Campos in Lisbon Revisited (1923)

Acknowledgements

To my parents,

for all the endless support they've given me.

To my grandparents,

who made possible for me to get here.

To my supervisors, professors Ana Carvalho and Bruna Mota,

for all the time invested in me and for allowing me to achieve better.

To Jorge,

for all the time I was unavailable for him.

To all interviewees,

who accepted to take part and were a key element for the development of this thesis.

To the Portuguese National Science Foundation (FCT) and Portugal 2020,

for the project LISBOA-01-0145-FEDER-028071 by UE/FEDER/FNR/OE.

To all who, in any given way, have contributed to make this become real,

my deepest and sincere **acknowledgements**.

Agradecimentos

Aos meus pais,

pelo infinito apoio que sempre me deram.

Aos meus avós,

por tornarem possível chegar aqui.

Às minhas orientadoras, professoras Ana Carvalho e Bruna Mota,

pelo tempo investido em mim e me permitirem chegar mais alto.

Ao Jorge,

por todo o tempo que não tive para ele.

A todos os entrevistados,

que aceitaram fazer parte e foram elementos-chave para o desenvolvimento desta dissertação.

À Fundação para a Ciência e Tecnologia (FCT) e ao Portugal 2020,

pelo projeto LISBOA-01-0145-FEDER-028071 da UE/FEDER/FNR/OE.

A todos os que, de uma maneira ou de outra, me permitiram tornar isto uma realidade,

*o meu mais sincero e sentido **agradecimento**.*

Abstract

As customers demand higher levels of service and societies call for direct action on sustainability topics, industries must adapt. Given the recent democratisation and diffusion of internet-based systems throughout the industrial fabrics, a new paradigm in manufacturing systems has been in vogue. They are becoming more digitalised, interconnected, and self-adaptive. Industry 4.0 will undoubtedly change the relationships between employers and employees, and business models, leading to new strains on both the environmental and social systems in which organisations are embedded.

This work aims, subsequently, at developing a decision-making supporting tool to assess, precisely, the impacts of the introduction of these technologies in the shop floor in terms of sustainability. For that, the outputting tool – **Sustainability 4.0** – is developed and presented. Its purpose is to identify the hotspots of the system under assessment so that a stakeholder engagement plan can be developed to mitigate or eliminate those exact hotspots. Additionally, a four-step methodology for its application is proposed from a user manual standpoint, offering a generic perspective to the application of the tool to any given case, sector-wise. The four steps encompass the definition of the scope of the assessment, the selection of the indicators, the development of a framework on which the tool is built, and the definition of the stakeholder engagement plan.

Moreover, an additional step, covering its validation, was included. For this work, a two-stage validation methodology was applied. Firstly, the tool was validated through a focus group with experts in the field. Then, in a second phase, the resultant pre-validated tool was further validated resorting to in-depth interviews with fifteen specialists from both the academic and business dimensions. Overall, the interviewees' reaction and receptivity to Sustainability 4.0 was overpoweringly positive whilst considering it makes a very strong case for the acclamation of Sustainability 4.0 as a tool that allows the assessment of sustainability impacts in a smart manufacturing context.

By enlarging the visibility of sustainability, it is expected that this work contributes to expand and consolidate research on a crucial topic, as well as to provide precious information to sustain decision-making processes.

Keywords:

Assessment;

Decision-making;

Indicators;

Industry 4.0;

Sustainability;

Triple bottom line.

Resumo

À medida que os níveis de serviço prestados se impõem cada vez mais elevados e a sociedade exige, cada vez mais, ações diretas em questões de sustentabilidade, as indústrias terão de se adaptar. Dada a recente democratização e difusão de sistemas continuamente ligados em rede nos tecidos industriais, um novo paradigma tem estado em voga – em particular na manufatura. As indústrias estão, por isso, a tornar-se cada vez mais digitais, interconectadas e auto-adaptativas. A indústria 4.0 irá, portanto, e certamente, provocar disrupções nas relações existentes entre empregados e empregadores, mas também nos modelos de negócio, resultando em novas pressões nos sistemas ambiental e social nos quais as organizações estão contidas.

Este trabalho tem como objetivo, subsequentemente, o desenvolvimento de ferramentas que suportem a tomada de decisões para aferir, precisamente, os impactos da introdução destas tecnologias nas operações das organizações ao nível da sustentabilidade. A ferramenta resultante – **Sustentabilidade 4.0** – é, assim, desenvolvida e os quatro passos que compõem a metodologia para a sua aplicação são apresentados na ótica de um manual de utilizador, oferecendo uma perspetiva genérica para a aplicação da ferramenta em qualquer caso, *i.e.*, independentemente do setor em que se está a aplicar. O seu propósito é a identificação dos pontos fracos do sistema sob aferição de modo a que um plano de envolvimento das partes interessadas possa ser desenvolvido de modo a mitigar ou eliminar esses mesmos pontos fracos. Os quatro passos da metodologia incluem, precisamente, a definição do âmbito da aferição, a seleção dos indicadores, o desenvolvimento do enquadramento da própria ferramenta e a definição do plano de envolvimento das partes interessadas.

Adicionalmente, foi incluído um outro passo que cobre a validação da ferramenta. Neste trabalho, uma metodologia de validação bifásica foi aplicada. Assim, a ferramenta foi, numa fase inicial, validada através de um grupo de foco com a participação de indivíduos cujo conhecimento na área é reconhecido. Já numa segunda fase, a validação anterior é complementada com entrevistas mais abrangentes com quinze especialistas na matéria quer da dimensão académica, quer da dimensão empresarial. De modo geral, os entrevistados rececionaram, de forma bastante positiva, o Sustentabilidade 4.0, considerado que foram apresentados argumentos robustos e válidos para a aclamação desta ferramenta como um instrumento que permite a aferição de impactos ao nível da sustentabilidade num contexto de indústria 4.0.

Ao alargar a visibilidade da questão da sustentabilidade, espera-se que este trabalho contribua para expandir e consolidar trabalhos de investigação anteriores num tópico crucial, assim como munir os decisores de informação na qual sustentar as suas decisões.

Palavras-chave:

Aferição;

Indicadores;

Indústria 4.0;

Sustentabilidade;

Tomada de decisões;

Tripé da sustentabilidade.

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Glossary

3BL: Triple bottom line;

AI: Artificial intelligence;

BoD: Board of directors;

Cobot: Collaborative robot;

CPS: Cyber-physical systems;

CSR: Corporate Social Responsibility;

CUR: Capacity utilisation rate;

DESI: Digital Economy and Society Index;

EBIT: Earnings before interests and taxes;

EU: European Union;

EVA: Economic value added;

GPS: Global Positioning System;

GRI: Global Reporting Initiative;

IChemE: Institution of Chemical Engineers;

ICT: Information and communication technologies;

Industry 4.0: Fourth industrial revolution;

IoT: Internet of things;

ISO: International Standards Organisation;

KPI: Key performance indicator;

LCA: Life Cycle Assessment;

LCI: Life Cycle Inventory;

LCIA: Life Cycle Impact Assessment;

LIDAR: Light Detection and Ranging;

NPV: Net present value;

OECD: Organisation for Economic Cooperation and Development;

PMI: Project Management Institute;

PRP: Performance reference point;

R&D: Research and development;

RADAR: Radio Detection and Ranging;

RFID: Radiofrequency identification;

ROA: Return on assets;

ROCE: Return on capital employed;

ROE: Return on equity;

ROI: Return on investment;

SEP: Stakeholder engagement plan;

SLCA: Social Life Cycle Assessment;

SME: Small and medium enterprise;

UNEP SETAC: United Nations Environmental Programme Society of Environmental Toxicology and Chemistry;

WHO: World Health Organisation.

1. Introduction

Sections 1.1. and 1.2. provide some initial insights and contextualise the work that was carried out. An overview of this dissertation and its structure are presented in sections 1.3. and 1.4., respectively.

1.1. Contextualisation and background

As society shifts towards a more digitalised way of functioning and as customers worldwide demand increasingly higher levels of service, industries across the world must adapt. This adaptation goes in favour of the current trends in automation, cloud computing, and cyber-physical systems (CPS) in which the ultimate goal is to obtain a more seamlessly connected and smarter ecosystem within a given industry to attain greater levels of productivity and efficiency overall (Kagermann *et al.*, 2011, 2013). This widely spread movement and awareness towards these recent technologies is often referred to as the fourth industrial revolution, industry 4.0, or even smart manufacturing. This recent and ongoing industrial paradigm, which focuses on a seamless integration between CPS, manufacturing operations, and information and communication technologies (ICT), is changing the rules of the competition, driving a transformation in current business models and shaping – or even creating – new demand patterns by customers (Dalenogare *et al.*, 2018). Several governments, including the Portuguese one, have developed programs to promote and foster these initiatives throughout the industrial fabrics of each country (Deloitte Portugal, 2017).

These new technologies and structural transformations will undoubtedly change the relationships between employers and employees, business models pursued by companies, and create new strains on both the environmental and social systems in which companies are embedded. The concept of sustainability appears here as the concern of balancing the pressures mankind puts in nature and its resources whilst pursuing the aspirations of having better life conditions and attaining greater levels of wellbeing (Brundtland, 1987). This concept, in its three dimensions, *i.e.*, social, economic, and environmental, is thus one of great importance when dealing with the fast-paced introduction of industry 4.0 technologies in both business and operational contexts.

As part of this new transformation era within industries, new technologies and equipment will disrupt the way employees perform their tasks, and impact, subsequently, the social and environmental systems that surround organisations. As a clear example of these impacts, collaborative robots (or cobots), for instance, are one of these technologies and have become an assiduous presence in modern factories and, consequently, a new source of disruption in the social landscape. These robots collaborate with humans in assembly lines and improve safety, productivity, and quality levels on site and throughout the value chain. Cobots, however, do not eliminate the need for human workers and, therefore, are not fully considered a form of automation, but rather as a way to ergonomically and more efficiently assist their tasks (Colgate *et al.*, 1996; Cherubini *et al.*, 2016).

Despite the research around the topic of industry 4.0, little or nothing is known about the impacts the introduction of these technologies will bring to our lives and to the environmental and societal ecosystems that surround a given organisation's operations (Kamble *et al.*, 2018). Therefore, it is important to study how sustainable this new industrial paradigm is, the associated impacts it will prompt upon implementation, and learn how to guarantee that this technological shift is performed in a sustainable manner.

1.2. Problem description

The topic of industry 4.0 is a relatively recent one, being the term first used only in 2011 (Kagermann *et al.*, 2011). This may help to explain why a systematic and comprehensive literature review has not been yet conducted, meaning that there is a lack of studies in this field (Lu, 2017; Kamble *et al.*, 2018). Moreover, since this industrial revolution will change relationships between employers and employees, business models, and create new strains in the social and environmental systems that surround organisations, there is a need to study how these new technologies will impact the future and how to employ them as sustainably as possible. Additionally, implementing these technologies on the shop floor level creates the need to develop new and suitable tools to assist decision-making processes in this field. This empowers decision-makers (or even policymakers) by helping them to make decisions that are sustained by data and facts.

This research project is an integrant part of the DM4Manufacturing project, a Portuguese-based project that focuses on the development of a new generation of industrial production systems with an emphasis on decision-making procedures based on ICT.

1.3. Purpose and objectives

The performed literature review, which will later be presented, underlined that research that combined the topics of sustainability and industry 4.0 is virtually inexistent and is merely focused on the environmental dimension. There were no records of research that provided an adequate, well-established, and comprehensive framework to assess sustainability, in all of its three dimensions, for industry 4.0 related topics. The conducted literature review and the critical analysis that followed also enabled to identify the subsequent problems:

- There are no clear, well-established, and standard metrics, indicators, or tools to assess sustainability in an industry 4.0 context;
- No comprehensive research on the topic, *i.e.*, on all of the three dimensions of sustainability, has been conducted in an industry 4.0 context;
- A standard Life Cycle Assessment (LCA) framework may not be adapted to accurately assess the environmental impacts of smart products nor may it be designed to resort to real time data as inputs;
- Some indicators, namely the ergonomics ones, require specialised equipment to measure them accurately;
- Subjectivity is inherently involved in the analysis, namely in the environmental and social dimensions;
- For the social dimension, there are no standard methodologies to assess social sustainability;
- A thorough and comprehensive analysis on sustainability requires the input of a great amount of data and some of which may be inaccessible to obtain.

This work aims to study the impacts of the introduction of industry 4.0 related technologies on the shop floor level from a sustainability standpoint. This will be performed in an industrial context, providing both a theoretical and pragmatic view on the topic. The output will be the development of a generic sustainability assessment and hotspot mitigation tool – **Sustainability 4.0**.

Firstly, this tool allows the identification and characterisation of sustainability hotspots derived from the implementation of these technologies. Secondly, following the identification of the hotspots, sets the future course of action for the development of a stakeholder engagement plan (SEP) to mitigate or eliminate them.

The tool was ultimately validated, in a primary step, through a focus group with experts in the field, and, subsequently, resorting to in-depth interviews, with another group of specialists from both the academic and business dimensions.

The goal of this dissertation is, therefore, to assess and outline how industry 4.0 technologies and the economic, environmental, and social dimensions of sustainability cohabit in a corporate environment and assess the impacts it prompted. Ultimately, this work aims, precisely, to fill the identified research gaps, providing an answer to the following question:

How to accurately and comprehensively assess the impacts of the introduction of industry 4.0 technologies in terms of the three dimensions of sustainability?

1.4. Structure

This dissertation is composed of seven chapters and an appendixes section:

- This present chapter provides a brief introduction and contextualisation of the topic that is going to be hereafter handled and states the purpose of the dissertation;
- The second chapter disserts on both the topics of industry 4.0 and sustainability, providing clear concept definitions and state-of-the-art reviews on both subjects;
- In the third chapter, useful and suitable indicators, tools, and metrics to assess sustainability in the context of industry 4.0, for each of its three dimensions, are proposed and described;
- Chapter four proceeds to present and explain the methodology of work followed for the development of Sustainability 4.0 and the subsequent stakeholder engagement plan;
- The fifth chapter focuses on the implementation of Sustainability 4.0 itself, providing a hands-on and practical guide on how to apply it to a real-life context;
- The sixth chapter covers the two-stage validation process of Sustainability 4.0;
- The seventh and final chapter is where the final conclusions are drawn, and future research work outlooks and considerations to further develop this work are suggested;
- The appendixes section contains the interview script that was used for the second stage of the validation process.

2. Industry 4.0 and sustainability: the dawn of a new era

Section 2.1. disserts on industry 4.0, providing clear concept definitions and a state-of-the-art review on the topic. Subsection 2.1.1. provides a contextualisation and explanation of industry 4.0 concepts whilst subsection 2.1.2. dives into a Portuguese perspective of the introduction of industry 4.0 technologies into the business context. Section 2.2., on the other hand, disserts on sustainability, providing, likewise, clear concept definitions and a state-of-the-art review on the topic. Subsection 2.2.1. provides a contextualisation and explanation of sustainability concepts whilst subsection 2.2.2. dives into the dissection of sustainability into three dimensions. Lastly, section 2.3. outlines this chapter's conclusions.

2.1. Industry 4.0

2.1.1. Background and definition of concepts

Kagermann *et al.* (2011), given the perceptible democratisation and diffusion of internet-based systems throughout the German industrial fabric, were the first to have coined the term "industry 4.0" as the brand of the fourth industrial revolution. The authors mention that CPS will lead the way to a paradigm shift in industries across the world. This original paper would, ultimately, build the basis to the industry 4.0 manifesto, which would later create the foundations to the spread this movement across several other countries that launched their own programs to develop and adopt these technologies (Kagermann *et al.*, 2013; Dalenogare *et al.*, 2018).

The concept of industry 4.0 is the current pinnacle of industrial breakthroughs that have been occurring over the centuries. The first industrial revolution occurred in the late 18th century. It was the moment in time where mechanical production sites, powered with water and steam, began to appear. The second industrial revolution followed the previous one, in the early 20th century, with the advent of mass labour production lines powered by electricity. More recently, in the 1970s, the third industrial revolution marked the start of automated production lines based on recent computerised-based technologies and electronics. Figure 1 summarises the timeline of industrial revolutions. Each revolution builds the foundations to the following ones. Industry 4.0 is, therefore, the product of all preceding turning points in the industrial fabrics across the global economies (Barreto *et al.*, 2017).

The term industry 4.0 eventually evolved to become an umbrella term, entailing, essentially, three dimensions (BITKOM *et al.*, 2015; Dalenogare *et al.*, 2018):

- 〉 An horizontal integration throughout the value chain where both intelligent intra and interenterprise links are formed, meaning that enterprises collaborate with each other by sharing resources and real time information;
- 〉 An end-to-end engineering across the product life cycle, meaning that engineering, connectivity, and technology are integrated in the product from cradle to grave;
- 〉 A vertical integration across value chain activities, meaning the embedding of ICT across the different hierarchical levels of an organisation, allowing a seamless integration between manufacturing and management levels.

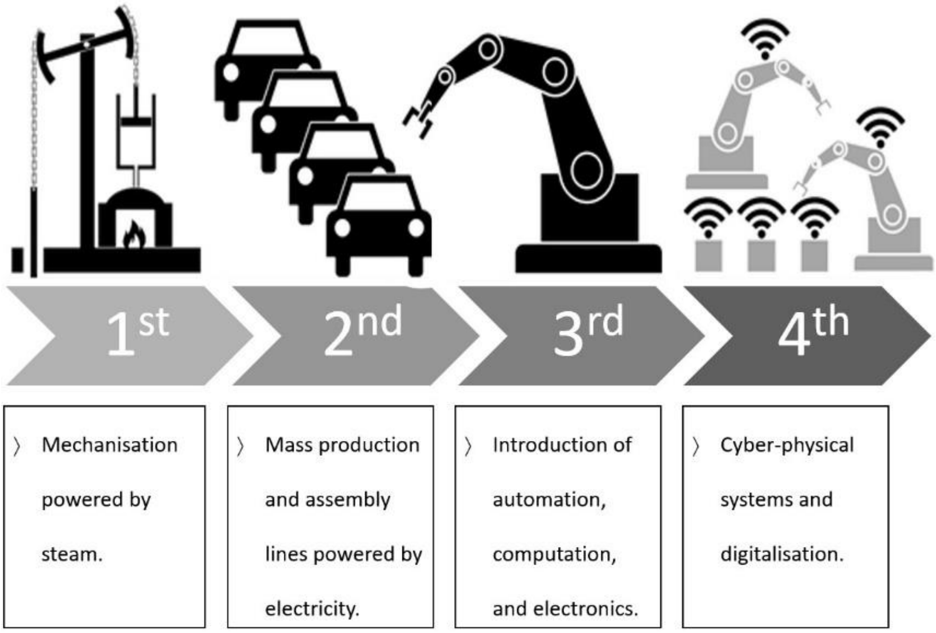

Figure 1 – Timeline of the industrial revolutions over the centuries (adapted from All About Lean, 2018)

All these crosslinks and digitalisation processes are made possible resorting to ICT permanently connected to the internet and to servers in a cloud. In a manufacturing process, these technologies are translated into the implementation of CPS operating in a decentralised and self-organised fashion, relying on the usage of mechatronic components such as sensors or other data collectors like the ones in table 1 (Horenberg, 2017). This data can be interchanged through the cloud in real time, contributing to intelligently link the CPS (Stock & Seliger, 2016). The concept of internet of things (IoT) appears here as an umbrella term for the ICT enablers of these crosslinks (Wang *et al.*, 2015; Jeschke *et al.*, 2017). It matters to say as well that the real time exchange of information potentialized by industry 4.0 technologies can occur between machines, between machines and humans, and also between humans since these have more data to support their communications, interactions and decision-making abilities (Kamble *et al.*, 2018).

Table 1 – Types of mechatronic components present in CPS (adapted from Horenberg, 2017)

Sensor type	Measurement purpose
Accelerometer	Acceleration of moving objects
Proximity sensors: LIDAR (Light Detection and Ranging), RADAR (Radio Detection and Ranging), and ultrasound sensors	Detecting ranges and distances to nearby objects
Temperature, humidity and barometer sensors	Environmental analysis
Time-of-flight cameras	Depth imaging
Vision cameras	Visual analytics, geometric dimensions and physical orientation
GPS (Global Positioning System)	Determining location
RFID (Radiofrequency identification)	Identification

It is expected that these technologies, when correctly supported and implemented, are able to contribute to an overall reduction in setup and processing times, costs in labour and materials, and higher levels of productivity and efficiency, whilst ensuring products with higher additional value. They are also bound to optimise resource usage, which will foster the development of more environmentally sustainable products and processes, and to introduce technologies that will change the role of the human being on the shop floor level (Kagermann *et al.*, 2011; Dalenogare *et al.*, 2018; FCT, 2018). Factories that implement these technologies are, within the nomenclature of industry 4.0, named smart factories, given their high resource usage efficiency, speed, and seamlessness in adapting to all changes by means of a feedback loop, meaning that the output is altered to meet the change exerted by the input or by previously set managerial goals and scenarios (Wittenberg, 2016; Kamble *et al.*, 2018). Likewise, smart factories manufacture smart products. These smart products have embedded technologies such as smart tags powered by radiofrequency identification (RFID), for instance. These tags hold information regarding the real time requirements for its subsequent manufacturing processes.

In manufacturing processes, technologies such as artificial intelligence (AI) and advanced and collaborative robots, for instance, can be disrupting factors in terms of sustainability. The implementation of these technologies must be performed in a way that values both the role of the human being within the smart factory and the environment by efficiently using resources and considering ecological designs into manufacturing, thus building the foundations for circular economies (FCT, 2018). The concept of collaborative robots, or cobots, is, for instance, particularly important to discuss and assess due to the changes they will bring to the way humans perform their tasks on the shop floor level. Cobots arose from the works conducted by Colgate *et al.* (1996), where they defined it as:

"(…) a robotic device which manipulates objects in collaboration with a human operator.".

According to the original authors, they are designed to assist a human operator in tasks where safety is a critical question, such as robot-aided surgery, or tasks were interaction forces are deeply involved, such as the lifting and handling of heavy objects in manufacturing industries. However, most current hybrid human-machine assembly systems are simply weight compensators which contribute to increase safety, quality, and productivity in a manufacturing site by reducing ergonomic concerns (Cherubini *et al.*, 2016). Maurice *et al.* (2017) state that cobots are useful in the reduction of musculoskeletal disorders that affect nearly 50% of industrial workers in developed countries.

Cherubini *et al.* (2016) additionally argue that, despite the increasing introduction of cobots in modern day industries, humans will not become obsolete, remaining an essential part in assembly operations. However, the authors argue that an advanced and more in-depth form of collaboration should be encouraged. They also claim that a crescent and massified demand for highly customised products requires an enormous amount of technological flexibility, suggesting that these hybrid manufacturing systems will be one of the enablers of this new wave of changes.

Liu *et al.* (2018) argue that traditional industrial robots, whilst being perfectly able to handle big packages and transport them, do not hold neither the aptitude nor the dexterity to take part in electronic manufacturing processes of products such as smartphones or electronic automotive components, presenting this constraint as one of the drivers to implement and integrate collaborative robots in modern factories. The authors present this fact to argue that, in some industries, the use of collaborative robots to assist humans in their tasks is still a better option than to just opt for fully automated ones. They additionally corroborate the argument provided by Cherubini *et al.* (2016) that the crescent variety of products requires technological flexibility.

Collaborative robot manufacturer FANUC reaffirms that integration of collaborative robots is different from implementing automation. FANUC argues that the implementation of fully automated systems is only effective when executed in cases where processes tend to be repetitive and tasks involving humans do not add any additional value. In cases where the strength, precision, and repeatability of a robot ought to be combined with the know-how, manual dexterity, and decision-making capacity detained by humans, collaborative robots are the best option (FANUC, 2017).

Though cobots have been around since the 1990s, the latest developments in ICT and sensors allowed these systems to evolve in the last few years (Cherubini *et al.*, 2016). Cobots are packed with all sorts of sensors, who provide real time data that can be used to make managerial decisions. These sensors also remove the need for these robots to be constrained within fences or other sorts of barriers in order to promote safety in the workplace since these devices are designed and packed with mechanisms that allow them not to harm any human.

Cobots are, unquestionably, a quintessential element of industry 4.0 technologies and are bound to change the dynamics of work and human-machine interaction in the shop floor but are simply the tip of the iceberg when it comes to disruptive elements this paradigm shift brings to light in terms of sustainability.

2.1.2. The Portuguese panorama

According to the 2018 Digital Economy and Society Index (DESI), an indicator designed by the European Union (EU) and whose goal is to assess and compare the level of digital performance among EU countries and whose results are summarised in figure 2, Portugal is considered an average performing country, with an overall grade slightly below the average one, occupying the 16th position (EU, 2018).

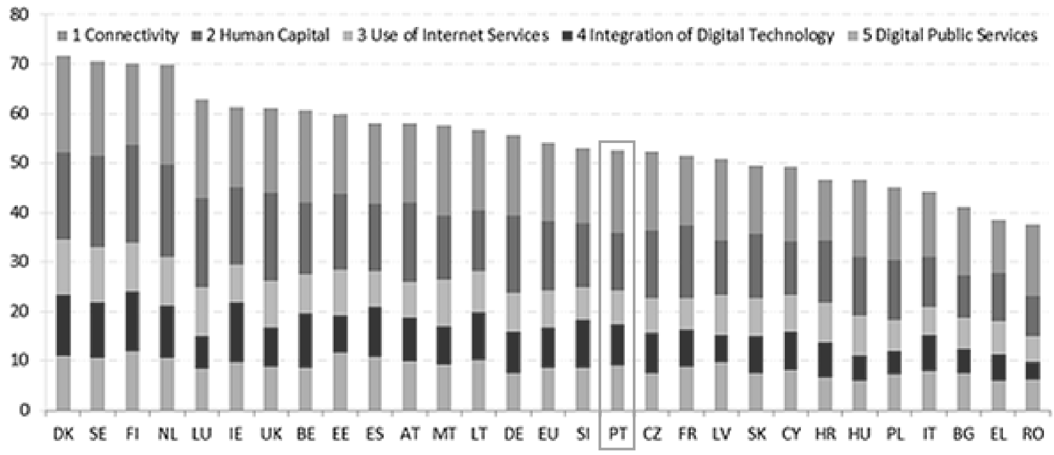

Figure 2 – DESI 2018 ranking with the Portuguese position highlighted (European Union, 2018)

An interesting finding of this report is that Portugal is one of the EU member states with the lowest share of professionals specialised in ICT, representing only 2,4% of total working population, a number that contrasts with the EU average of 3,7% (EU, 2018). Qualified and skilled labour is a matter of great importance when it comes to industry 4.0 since the shortage of workers who possess the necessary qualifications may be an obstacle to the correct implementation of industry 4.0 technologies in a business context (Wegener, 2015). Another study by

UBS shows that the Portuguese economy ranks as the 23rd (out of 45) most ready to adopt industry 4.0 technologies (UBS, 2016) and an additional one, by Deloitte, indicates Portuguese enterprises have a third of the robots (per 10.000 employees) when compared to the Spanish ones (Deloitte Portugal, 2017). This reasonable degree of readiness contrasts with its current competitiveness: Portuguese industry ranks at the 35th most competitive economy out of 40. The industry 4.0 trend thus poses as a clear opportunity to overcome the existing barriers to the expansion of the economy (*e.g*. peripheral geographic location and unscalable internal market). Given this, in 2017, the Portuguese Ministry of Economy introduced the initiative "Portugal i4.0" whose goals are to identify the needs of the Portuguese industrial fabric and coordinate appropriate measures to accelerate the adoption of industry 4.0 technologies and to make Portugal an attractive ecosystem for investments in this field. This follows the same line governments from other EU and non-EU countries have been applying (Deloitte Portugal, 2017). This industrial modernisation, scheduled to occur in the next couple of decades, is meant to support the ability to innovate, placing innovation as the main driver for an increase in competitiveness (FCT, 2018).

The topic of industry modernisation via digitalisation of the Portuguese industrial fabric is, consequently, one of great relevance to the economic sustainability of the country. In Portugal, one of the main factors of economic growth is exportations. Products from manufacturing industries account, as of 1Q 2017, for 94% of the total amount exported (FCT, 2018). Given the cruciality of the subject, it matters to create the foundations for a robust and sustainable implementation of industry 4.0 technologies in the long run.

2.2. Sustainability

2.2.1. Background and definition of concepts

The term sustainability was first used, with a similar meaning as the current one, in the forestry field, denoting the act of not cutting more trees than the ones a forest yields (Duerr & Duerr, 1971). However, the concept of sustainability as a policy and as a research topic boosted after the release of the Brundtland report (Brundtland, 1987) in which the concept of sustainability was defined as the concern of balancing the pressures mankind puts on nature and its resources whilst pursuing the aspirations of having better life conditions and attaining greater levels of wellbeing, *i.e.*, in its own terms:

"*(…) development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*".

More recently, and as more research has been done on the topic, the concept evolved into an umbrella term, entailing three dimensions: economic, social, and environmental (Kuhlman *et al.*, 2010). Cato (2009) argues that, out of these dimensions, the environmental is the one that, ultimately, constrains the remaining two, as shown in figure 3. This enclosure of dimensions into one another derives from the fact that there are flows of resources between each layer, meaning that the economic layer is constrained by the social systems surrounding it and both the economic and social layers are constrained by the existing natural resources. This partitioning of the concept of sustainability comes, mainly, from the works of John Elkington when designing the triple bottom line (3BL) concept (Elkington, 1994; Elkington, 1998). In an organisational context, the operationalisation of sustainability defines the concept of sustainable development. Here, the three dimensions can be translated to social equity, economic efficiency and environmental performance (Labuschagne *et al.*, 2005).

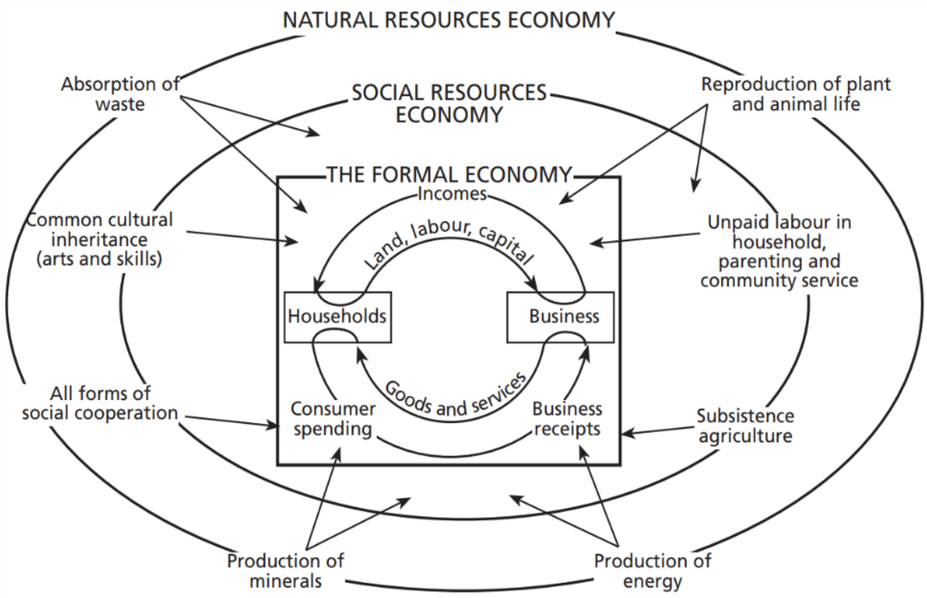

Figure 3 – The three dimensions of sustainability (Cato, 2009)

Despite the research that has been done on the topic over the last three decades, there is a general sense that the concepts of sustainability and sustainable development lack a clear and unequivocal standardisation and definition. This fact is more conspicuous in the field of social sustainability due to the cultural and ethical differences existing around the world and the fact that there are not clear key performance indicators (KPIs) to measure, evaluate, and, consequently, compare how much more sustainable a given organisation is on a comparative basis (Simões, 2014). This may be one of the reasons why companies continue to disregard environmental and social issues in opposition to the economic one (Pagell & Shevchenko, 2014).

Increasing environmental pressures and generalised social disparities triggered by global development are the main drivers for the promotion of *sustainable-development-oriented* business models in industries across the world, but their implementation is not yet satisfactory. This is mostly due to the struggle enterprises and academics have in correctly and objectively use indexes to measure sustainability. These tools can provide a solid ground to support decisions and implement new strategies, thus being a relevant topic to decision-making (Waas *et al.*, 2014).

PRé Sustainability is a Dutch consulting company that focuses on helping other enterprises to create sustainable business value by supporting sustainability with metrics. When asked about how to measure sustainability, one of their consultants replied:

"Sustainability has evolved much farther than just measuring carbon emissions, which means it requires management of many factors. There are a multitude of impacts to consider: impacts on water use and water supply, impacts on human health, and even social impacts on workers and communities." (PRé Sustainability, 2014b).

Additionally, the company defines a sustainability index as a piece of information that can be used from the managerial point of view to support and strengthen the decision-making process. It is meant to aggregate data about the sustainability aspects of several decisions, strategies, and approaches, having the final goal of determining what is the most sustainable option. A sustainability index can be tailored and customised according to the needs of an enterprise and the characteristics of the type of industry or sector in which it operates. PRé Sustainability (2014b) also provides a generic four-step methodology on how to perform it. It should then be tailored to the needs of the organisation that wishes to use it. The first step of this generic methodology is to define which factors are important to the company and its stakeholders and should, therefore, be included in the assessment (*e.g.* carbon emissions, air quality impacts, impacts on local communities, workers wellbeing, *etc.*). They should then be prioritised according to the level of importance the company considers them to be. The second step is the scope definition, *i.e.*, the definition of which decisions will be made having the indexes in consideration. This is also the step where the data sources should be considered, and data should be collected. The third step is the construction of the index itself. Using the previously defined objectives and the prioritisation, weights and scales ought to be defined to evaluate a given aspect and obtain a final single score. The fourth step is simply the fine tuning of the factors, weighting, and scoring systems to accurately translate the information into tools that allow to make sustainable decisions.

The purpose of building a sustainability index is to embed it into the decision-making process. Several organisations have been building their own customised sustainability indexes for their own purposes. BASF, a German chemical product manufacturer, for instance, has developed its own index to grade its products in terms of sustainability. This index – the Eco-Efficiency Analysis – considers the environmental impacts in proportion to the product's cost-effectiveness, which is then translated into a final single score that is easily understood by all (BASF, 2016). The SEEbalance® analysis is an extension of this tool that additionally includes social aspects by resorting to a Social Life Cycle Assessment (SLCA). The result of the application of this analysis is a plot of the sustainability performances in each dimension (BASF, n.d.).

In conclusion, measuring sustainability is a complex task that presents many challenges, but using a meticulously tailored index and/or methodology can help to reduce misunderstandings and allow to streamline and strengthen the decision-making process.

2.2.2. Triple bottom line

In an attempt to create a standardised framework to include environmental and social aspects in traditional KPIs, such as profit and other typically economic-wise indexes, Elkington (1994, 1998) designed the triple bottom line philosophy which integrates the three dimensions of sustainability (economic, environmental, and social) in a measurement of organisational performance. This framework accounts the three dimensions in an egalitarian manner, *i.e.*, when used in decision-making, they all have the same level of importance (Beske, 2012).

Despite a more thorough and extensive definition and literature revision of each of the three aforementioned dimensions being provided in the third chapter, the following sections briefly describe each of the three dimensions of sustainability.

The economic dimension

The Global Reporting Initiative (GRI), an international standards organisation specialised in consulting and advisory services in topics related to climate change and other social issues, defines the economic dimension of sustainability as the effects that a given organisation prompts in the economic conditions of its stakeholders (GRI, 2016a, p. 4). It is the dimension that is primarily spoken about when handling sustainability and sustainable development concepts within the business context since it is the one that, without attaining it, the organisation cannot survive, ending up always being put in first plane at the cost of disregarding the other two dimensions (Pagell & Shevchenko, 2014).

This dimension of sustainability can be easily measured since there is a large number of KPIs (*e.g.* return on investment, profit, turnover, *etc.*) that can simply be collected from, for instance, financial statements and other accounting documentation. This information allows, consequently, to compare how much more sustainable, from the economic and financial point of view, is one business from another. This vast availability of tools to measure economic sustainability in comparison to the other dimensions may explain the considerably greater attention this dimension receives from a corporate point of view (Kocmanová *et al.*, 2011). The GRI itself proposes its own set of KPIs to assess economic sustainability such as wages, operating costs, capital costs, *etc.* (GRI, 2016a). Al-Sharrah *et al.* (2010) argue that each industry has its own specific KPIs that enable a thorough assessment of the economic status of a business. The Organisation for Economic Cooperation and Development (OECD) (2008) additionally proposes cost *vs.* benefit analysis, modelling, regressions tests, and scenario analysis as other varieties of tools to assess economic sustainability.

The environmental dimension

When thinking of sustainability, the environmental dimension is, most likely, the one that immediately comes to the top of one's mind. The GRI defines the environmental dimension of sustainability as the effects an organisation prompts on living and non-living natural systems, which includes the ecosystems (GRI, 2016b, p. 4). It accounts for the usage of natural resources, energy, waste management, carbon footprints, and other related concepts.

OECD (2008) presents a number of environmental sustainability assessment tools such as Life Cycle Assessment (LCA), material flows, accounting of resources, *etc.*. A more thorough and extensive definition of LCA is provided in the third chapter given the relevance it has won throughout the years in both academia and industry. This adherence to LCA derives from the fact that it is the most reliable and well-established tool to assess environmental impacts and support claims whilst complying with well-defined standards (European Commission, 2016; ASMI, 2018).

The social dimension

The social dimension of sustainability is the most disregarded one due to the lack of clear and unequivocal KPIs that allow to measure and assess it, but also because businesses fail to understand the integration of this dimension as part of sustainable development (Pagell & Shevchenko, 2014). The GRI defines it as the effects and impacts a given enterprise has on the social systems in which it operates (GRI, 2016c, p. 4). The United Nations (UN) (2017) additionally defines it as follows:

"*Social sustainability is about identifying and managing business impacts, both positive and negative, on people. The quality of a company's relationships and engagement with its stakeholders is critical. Directly or indirectly, companies affect what happens to employees, workers in the value chain, customers and local communities, and it is important to manage impacts proactively."*.

OECD (2008) presents a number of sustainability assessment tools such as sustainable livelihood, human and social capital measurement and participatory processes.

2.3. Chapter conclusions

This chapter began by describing the concept of industry 4.0. Industry 4.0 is an umbrella term for the current and ongoing trend in making the shift to a more digital and interconnected industrial ecosystem. It is also the culmination of all three preceding industrial revolutions. The cornerstones of this transformation are the CPS, that make the link between the real and the virtual worlds by means of mechatronic components, such as RFID tags, and the IoT, enabling the interconnectivity between these systems. This lays the foundations for the rise of smart factories and smart products. The introduction of these technologies on the shop floor level is also bound to disrupt business models pursued by companies, change the relationship between employers and employees, and the way people perform their tasks. The role of the human being within the smart factory will, therefore, suffer transformations and the economic, social, and environmental ecosystems in which the factory is embedded will be affected. The literature pointed out that technologies such as collaborative robots will be one of those disruptive drivers, changing the way machines and humans interact. Lastly, findings show that the Portuguese economy might not be well adapted to incorporate these technologies into its industrial fabric but that this crescent awareness towards the topic might be the opportunity it needed to leverage it. This is why the concept of sustainability – in all of its three dimensions – plays a significant and prominent role, here.

The second part of the chapter dove, precisely, into the topic of sustainability, offering a description of the concepts that surround it. Since the Brundtland report, in 1987, sustainability has taken successively higher places at the decision-making table. Sustainability is often considered as an onion-shaped concept, composed of three successively entailing layers: the economic layer, the social layer, and the all comprising environmental layer. This tripartite view of sustainability is known as the triple bottom line. Lastly, findings showed that sustainability is difficult to measure in a clear and unequivocal way due to its ubiquity and lack of standardisation and definition. Because of that, both social and environmental dimensions end up being disregarded in opposition to the economic one. To overcome this, tailored sustainability indexes can be developed.

Given this, it is important to focus the course of this work into finding appropriate sustainability indicators, KPIs, and assessment tools, for all of the three dimensions, that fit into the topics of industry 4.0 and smart manufacturing. The third chapter, therefore, covers this quest.

3. Assessing sustainability in a smart manufacturing context

This chapter disserts on suitable sustainability metrics and tools for an industry 4.0 context, providing clear concept definitions and a state-of-the-art review on the topic. Section 3.1. provides a contextualisation and explanation on how to assess economic sustainability, section 3.2. dives into the topic of assessing environmental sustainability, and section 3.3. disserts about assessing social sustainability and its fittingness for industry 4.0 topics. Section 3.4., on the other hand, plunges into the intertwining of the topics of industry 4.0 and sustainability. Lastly, section 3.5. outlines this chapter's conclusions.

Assessing sustainability in a clear and unequivocal way has proven to be a difficult task due to the high amount of subjectivity and lack of standardisation involved in the process, especially when it comes to the environmental and social dimensions. There is, therefore, a need to identify and determine which indexes, tools, KPIs, and methodologies are most suited to fulfil this task. Each dimension has its own appropriate indicators to ensure they are correctly used in decision-making processes that may arise from making the shift to industry 4.0 a more sustainable process overall. What follows is an overview of frameworks, tools, and indicators used to assess sustainability in each of its three dimensions and an appraisal of their suitability to tackle this issue in a smart manufacturing context.

3.1. Economic dimension

The economic performance of an organisation is crucial to guarantee its long-term survivability and also a cornerstone of any organisation's sustainability. For this reason, it is the dimension enterprises typically measure and control whilst disregarding the remaining two (Pagell & Shevchenko, 2014). One of the reasons for the disregard of the social and environmental dimensions is, precisely, the accessibility and availability of information that allows to effortlessly measure and assess this dimension in particular. Data regarding the economic performance of any organisation can be found by looking into its financial and accounting statements which are, most of the times, demanded by law (GRI, 2011). These documents provide information regarding the current performance and position of the company, the changes in performance it may have, among several other important economic and financial indicators (Dias, 2014). The GRI (2011) and Dias (2014) additionally state that reports regarding an organisation's economic performance may provide information on whether or not its financial viability is achieved at the cost of creating significant externalities that may affect several stakeholders. However, what is often less reported, and is frequently desired by users of sustainability reports, is the organisation's contribution to the sustainability of a larger economic system (GRI, 2011).

Indicators regarding the economic dimension of sustainability are, therefore, and in this context, intended to assess, evaluate, and measure in what way and to what extent the economic performance is altered when implementing and employing industry 4.0 related technologies within the organisation. The information condensed in the several indexes will, ultimately, highlight the flows of capital between several stakeholders and the main economic impacts the organisation has in the societal ecosystem it is embedded into (GRI, 2011; Dias, 2014; IChemE, n.d.).

An economic impact can be defined as a change in the productive potential of the economy that has an influence in the community, the stakeholder's well-being, and/or longer-term prospects for development (GRI, 2011). In an industry 4.0 context, to analyse the potential economic impacts that the introduction of these technologies might have prompted, it is important to make a comparative evaluation of the period prior to that introduction with the moment after. What follows is a listing of common indicators and tools used by some influential entities, such as the GRI and the Institution of Chemical Engineers (IChemE) – both renowned institutes that develop reports on sustainability topics –, to assess the impacts regarding the economic dimension.

3.1.1. Profitability and investment analysis

The adoption and implementation of industry 4.0 technologies on the shop floor level implies a great financial effort by organisations (Kagermann *et al.*, 2011, 2013). Therefore, it is important to assess to what extent these investments have contributed to add value. This is where investment analysis enters the discussion.

Investment analysis can be understood as an umbrella term that comprehends the evaluation of financial or material assets. It is particularly useful to analyse future performance of past investments and to select the type of investment instrument that best suits the needs of an investor. The outputs of any investment analysis are meant to be used as inputs to related decision-making processes (DeFusco *et al.*, 2015) and a key element of economic sustainability since the identification and selection of good investments is fundamental for a sustainable and successful future (Mota, 2015).

The IChemE (n.d.) and Weber *et al.* (2008) propose a list of investment analysis indicators that are suitable to address sustainability issues:

Return on assets

Return on assets (ROA) indicates the extent of profitability of a company regarding its total assets, *i.e.*, how efficiently an organisation is using its resources to make a profit. The higher the ROA, the higher its efficiency in asset utilisation. It is computed by dividing an organisation's net income by its total yearly average assets, as equation 1 shows, and can be expressed in percentage (Hargrave, 2019a).

$$\text{ROA} = \frac{\text{Net income}}{\text{Yearly average assets}} \tag{1}$$

Return on equity

Return on equity (ROE) compares the profit that is made available to shareholders with the capital provided or owned by them. Whilst ROA is more important from the internal point of view, ROE is what external investors tend to look at. The higher the ROE, the higher the chances for attracting investors. It is computed by dividing an organisation's net income by its yearly shareholder equity, as equation 2 shows, and can be expressed in percentage (Hargrave, 2019b).

$$\text{ROE} = \frac{\text{Net income}}{\text{Yearly average shareholder equity}} \tag{2}$$

Return on capital employed

Return on capital employed (ROCE) is useful to assess and compare how profitable a company is. It measures how efficiently an organisation is using its own financial resources to generate profits. It is computed by dividing an organisation's operating income (EBIT) by the difference between total yearly average assets and total yearly average liabilities, as equation 3 shows, and can be expressed in percentage (Kenton, 2019b).

$$\text{ROCE} = \frac{\text{EBIT}}{\text{Yearly average assets - Yearly average liabilities}} \tag{3}$$

Return on investment

Return on investment (ROI) is a centrepiece of any investment analysis. It measures the efficiency of a single investment or can compare the efficiency of multiple investments. It measures, in a very direct and straightforward way, the return that results from a particular investment relative to its cost. It is computed by dividing the difference between the benefit (return) of the investment and its respective cost by its respective cost, as equation 4 shows, and can be expressed in percentage (Chen, 2019).

$$\text{ROI} = \frac{\text{Return of investment - Cost of the investment}}{\text{Cost of the investment}} \tag{4}$$

Net present value

Net present value (NPV) assesses the difference between cash inflows and cash outflows over a certain period of time, namely the period of time the asset remains in an organisation's possession. Inflation rates and hypothetical returns from alternative investments which could be made during the intervening time explain the fact that 1€ in the present is not worth the same as 1€ at a given point in the future. Therefore, there is a need to take into account present values for the cash inflows and outflows instead of nominal values. A positive NPV indicates that the projected returns of the investment have exceeded the anticipated costs whereas a negative NPV suggests a net loss has resulted from the investment (Kenton, 2019a).

NPV can be computed taking into account a series of cash flows within specific and equally spaced time frames, usually a year or a month. Mathematically, NPV is computed by equation 5 and can be expressed in monetary units.

$$\text{NPV} = \sum_{i=0}^{T} \frac{C_i}{(1+r)^i} \tag{5}$$

Where:

r – Discount rate;

i – i^{th} period of time;

C_i – Net cash flows that have occurred in the i^{th} period of time;

T – Total periods of time considered.

Economic value added

The economic value added (EVA) measures, alongside with the net profit, an organisation's financial performance by calculating the residual wealth, which can be obtained by deducting the cost of capital from its operating profit. It captures the true economic profit of a company by measuring the value it generates given the funds invested in it. It can also be interpreted as an indicator of the amount of wealth an organisation created for its stakeholders, including revenues, employee compensation, donations and other community investments, retained earnings, and payments to capital providers and/or governments via payment of taxes (GRI, 2011).

The data required to compute an organisation's EVA should be collected from financial documents (*e.g.* balance sheets, profits and losses statements, *etc*.) and/or internally audited accounting information. If applicable, the EVA should be computed at a regional level whenever a company operates in several sites across a given country (GRI, 2011; Dias, 2014; IChemE, n.d.).

3.1.2. Productivity and quality

One of the premises of the implementation of industry 4.0 technologies in the shop floor is the expectation that they will contribute to reduce setup and processing times, costs in labour and materials, higher levels of productivity and efficiency, as well as an increase in quality standards (Kagermann *et al.*, 2011; Dalenogare *et al.*, 2018; FCT, 2018). Productivity and quality metrics are, therefore, a centrepiece of any organisation's economic sustainability (Bleischwitz *et al.*, 2009) and, in the context of analysing the impacts of industry 4.0, acquires an even higher importance.

Some productivity and quality indicators and KPIs can be found in the literature, sustainability reports, and in some organisation's performance reports (GRI, 2011; IChemE, n.d.; Bleischwitz *et al.*, 2009).

Throughput time

In a manufacturing process, throughput time corresponds to the total amount of time required for a product to undergo a manufacturing process, *i.e.*, the elapsed time between the conversion of raw materials into finished goods (Plossl, 1988). Throughput time can be segmented into four periods of time:

- **Processing times** – time spent in transforming raw material into finished goods;
- **Inspection times** – time spent in the inspection of raw materials, work in progress, and finished goods;
- **Move times** – time spent in the movement of material within the manufacturing area;
- **Queue times** – time spent in idle processes (*e.g.* waiting for precedent processes to finish or waiting to be inspected).

The sum of these time periods corresponds to throughput time.

Capacity utilisation rate

One way to straightforwardly address the question of productivity is to compare the effective output of an organisation with its installed productive capacity, *i.e.*, to what extent are the resources of a company being used compared with its maximum performance. This is exactly what capacity utilisation rate (CUR) aims to measure. It is a measure of operating efficiency and organisations with a CUR of less than 100% can, theoretically, increase production at no expense of rising overhead costs (Greenwood *et al.*, 1988). It can be mathematically translated into the division of the effective current output with the potential maximum output, as equation 6 shows. It can be expressed in percentage.

$$\text{CUR} = \frac{\text{Effective current output}}{\text{Potential maximum output}} \tag{6}$$

Scrap rate

One way to assess quality in a manufacturing system is to look at the number of units that were produced, *i.e.*, got to the end of the manufacturing process, that had to be scrapped due to defects or errors. Therefore, scrap rate measures, precisely, the ratio between the number of units that were scrapped during the production process and the total number of units produced during the same period of time, as equation 7 shows (Hallmann *et al.*, 2018). It can be expressed in percentage.

$$\text{Scrap rate} = \frac{\text{Number of units scrapped}}{\text{Total number of units produced}} \tag{7}$$

Defect rate

Another quality KPI is defect rate, which measures the number of units produced that have failed to meet a predetermined quality target. It is used to assess and control non-compliances. Quality targets can be organisational managerial goals, defined internally, or can be mandatory requisites stated either by specific legislation or industry standards. Mathematically, it can be translated to the ratio between the number of units that have failed quality tests and the total number of tests that have been conducted, as equation 8 shows (Harris, 1968). It can be expressed in percentage.

$$\text{Defect rate} = \frac{\text{Number of units that fail test}}{\text{Total number of tests conducted}} \tag{8}$$

3.1.3. Financial implications

The GRI (2011) employs this category to assess the financial implications, risks, and opportunities for the organisation's activities that are associated to climate change. Climate change implies risks and opportunities to organisations and to all intervenient stakeholders. The expected increase in energy expenditure with the introduction of industry 4.0 technologies may be troublesome if these changes affect, for instance, power grids. The category also includes risks such as the increase in the frequency of storms and other extreme weather events, sea level changes, increase of overall temperatures, and availability of water. The operations of an organisation may, much more likely, suffer disruptions with these risks. Another risk that poses a threat to the financial health of a company are the increasing regulatory pressures imposed by governments in an effort to regulate activities that contribute to climate change. This regulatory risk can be responsible for an increase in costs, impacts in productivity, and, consequently, competitivity (GRI, 2011; Dias, 2014). These last two authors also argue that eventual restrictions and limitations regarding greenhouse gases emissions may create opportunities for organisations to resort to new and innovative technologies which may, in its turn, make way to operate in new markets.

3.1.4. Financial autonomy

This indicator assesses the degree of dependability an organisation has regarding governmental contributions, *i.e.*, it measures the amount of funds received by a company that have come from State-owned organisations. These contributions need to be compared with the amount of taxes payed by the receiving organisation. The transactions of capital, in order to be considered in this indicator, must not correspond to the exchange of goods and services but to the incentives and compensations for actions taken or costs of a given asset, meaning that these incentives represent a significant form of financial aid and that the State does not expect a direct form of reimbursement for that (GRI, 2011).

3.1.5. Local community practices

Any policies, practices, and the proportion of expenditure an organisation has regarding other local enterprises and communities are taken into account in this economic impact category. By settling into a given region, the influence sphere of an organisation covers much more than the direct jobs and payment of wages to its employees since it also covers the surrounding enterprises that may interact with it (*e.g.* suppliers, partners, *etc.*). These interactions may be responsible for the creation of additional value that may attract additional benefits to the region (GRI, 2011; Dias, 2014). With industry 4.0, enterprises along the value chain are bound to become more collaborative (BITKOM *et al.*, 2015; Dalenogare *et al.*, 2018). If the companies along this chain are located in the same region, chances are that they may be benefited from the economic point of view due to the possible creation of synergies and the expected horizontal integration, one the premises of industry 4.0.

Additionally, the GRI (2011) considers the proportion of people who are residents from neighbouring areas and are hired as an indicator of sustainable economic impact. The hiring of local and experienced people may benefit the region since they hold a general bigger understanding of the societal and environmental systems the organisation is embedded in, reinforcing the economic benefits to local communities.

3.1.6. Direct and indirect economic impacts

Investments made by organisations, whether by commercial involvement or *pro bono* activities, that impact the general public are considered in this category as a direct economic impact. Investments in infrastructures, services, and the overall distribution of created economic value can affect the surrounding economic ecosystem and can be seen as a way for organisations to compensate any externalities they may be responsible for (GRI, 2011; IChemE, n.d.).

As to what indirect economic impacts are concerned, this impact category identifies and describes the effects of transactions of value between the organisation and its stakeholders. Indirect economic impacts can be monetary or non-monetary and are particularly important to assess in relation to local communities and regional economies. Examples of indirect economic impacts are the improvement (or deterioration) of social and environmental conditions, such as changing the job market in a given region, the economic impacts of pollution, or changes in the productivity of organisations – or even the whole economy overall – by means of a greater adoption of ICT (GRI, 2011; Dias, 2014).

3.2. Environmental dimension

The topic of sustainable manufacturing has been in vogue since it branched out from the Brundtland report (Brundtland, 1987) and several subsequent works conducted by the UN such as its 2030 sustainable development agenda (UN, 2015). Additionally, increasing regulatory pressures by governments on organisations have forced them, especially those that operate in manufacturing industries, to implement and pursue greener technologies and processes in their operations. Given this, a greater understanding of environmental impacts of services and products is required (Gregori, 2017).

In the last few decades, given the increasing burden of regulatory pressures, industries have made efforts in order to develop processes, practices, and, ultimately, products that are more environmentally friendly. To achieve this, however, it is essential to have a complete assessment, from the resource point of view, of the operations involved in manufacturing. This is where LCA enters the discussion as a methodology that is used to assess the environmental performance of a given process, product, or service. LCA is widely used by enterprises and academics who intend to evaluate how green their activities are, whether for benchmarking purposes, for legal compliance, or even for marketing reasons (European Commission, 2016; Dias, 2014; ASMI, 2018).

3.2.1. Life Cycle Assessment

LCA is a standardised and well-established methodology used to assess how a given product, process, or service impacts the environmental and social spheres in all of its life cycle, *i.e.*, from the extraction of raw materials needed to its manufacturing to the end of life phase and consequent waste management procedures (Raihanian & Behdad, 2018). It mainly focuses on the identification and quantification of inputs and outputs that integrate the life cycle (ISO 14040, 2006; ISO 14044, 2006). The International Standards Organisation (ISO), in response to the increasing demand of information and standardisation on the topic, created the ISO 14000 family of standards which are related to environmental management. The ISO 14040 and ISO 14044 standards build the foundations for a standardised LCA framework, defining its requirements, goals, and scope (ISO 14040, 2006; ISO 14044, 2006). An LCA study is comprised of four phases, schematised in figure 4.

There are different methods to operationalise an LCA. Each consider a disparity of impact categories, emission factors, and normalisation and weighting techniques, making the comparison between the single scores obtained by different methods a tricky task (Pennington, 2005; Simões, 2014). Despite being a widely accepted tool and put in practice in both academic and business contexts, LCA has its flaws, especially when it comes to the uncertainty, subjectivity, and complexity involved (Raihanian & Behdad, 2018).

LCA can also be defined as a tool that assesses the environmental impacts and resources used throughout a product's life cycle, *i.e.*, from the acquisition of raw material to the production, use and waste management phases (Finnveden *et al.*, 2009; European Commission, 2016; Dias, 2014; ASMI, 2018). LCA is a widely used and internationally standardised methodology that quantifies the environmental pressures that a given good or service has on the environment. It lists the environmental benefits, the trade-offs, and identifies areas for achieving improvements (ISO 14040, 2006; ISO 14044, 2006; European Commission, 2016).

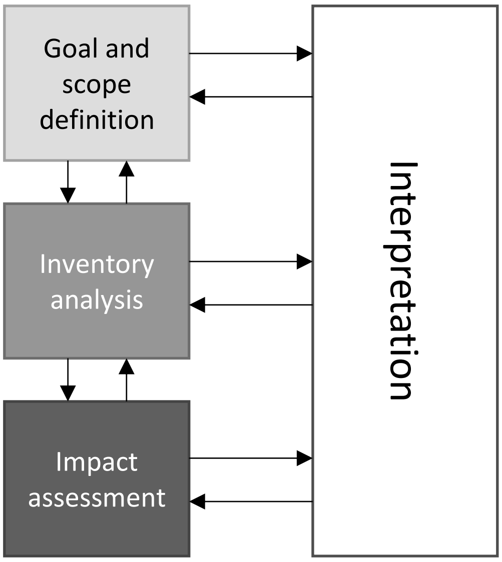

Figure 4 – The LCA framework (ISO 14040, 2006)

The core of LCA is comprised of two sequential phases (European Commission, 2016):

〉 **Life Cycle Inventory (LCI)** – collection and analysis of data regarding the environmental interactions (*e.g.* emissions to air or water, generated waste, consumption of resources, *etc.*) is performed. The data is related with the extraction of raw material, consumption of resources, release of emissions throughout production, and end of life procedures, for instance;

〉 **Life Cycle Impact Assessment (LCIA)** – estimation of indicators of environmental pressures in terms of, for instance, climate change, summer smog, resource depletion, acidification, human health effects, *etc.*, associated with the environmental interactions attributable to the life cycle.

This methodology has the ultimate goal of evaluating the impacts associated to the use of a product, of a given process, or an overall system. If the application of an LCA methodology is being made to a system, a frontier needs to be clearly and unequivocally defined (ISO 14040, 2006; ISO 14044, 2006; Ferreira, 2004). This methodology involves the compilation and measurement of all inputs, outputs, and impacts on the environment that surround a system throughout its entire life cycle, *i.e.*, from cradle to grave. Figure 5 schematises what is involved in the system-thinking philosophy of any LCA.

The complexity involved in the correct implementation of this methodology leads to the need of limiting the inputs and outputs of the analysis in order to underwhelm it, meaning that only the inputs and outputs that are relevant to a predetermined objective are taken into account (Browne *et al.*, 2005). However, all LCA methodologies, regardless of their purpose, must follow the systematic approach described in figure 4.

The first step of this methodology, schematised in figure 4, is scope definition. Here, the object of analysis (*e.g.* system, products, processes, *etc.*) and the boundary of the system are defined, alongside with the determination of the goals of the analysis. In the second stage, the inventory analysis, a listing of all inputs and outputs of the system to be analysed is performed. With this, the analyst can have access to accurate data regarding the required resources and respective emissions, *i.e.*, energy and materials, for each stage of the life cycle. The following step is impact assessment, in which the most relevant environmental impacts throughout the life cycle are assessed. There are several methods that allow this assessment – some of which will be discussed in more detail, later on. Lastly, in the interpretation phase, the results of both the inventory analysis and impact assessment are compiled and evaluated so that a decision on what is the best product, process, or service, in environmental terms, is taken (ISO 14040, 2006; Ferreira, 2004). This information can be, ultimately, used to assist decision-making processes, to foster the development of more sustainable products/processes, to comply with governmental policies and regulations, or even for marketing reasons, as demand for increasingly more sustainable products is on the rise (European Commission, 2016; Dias, 2014; ASMI, 2018).

What follows is a more comprehensive review of the LCIA phase, focusing on the available methodologies to perform it.

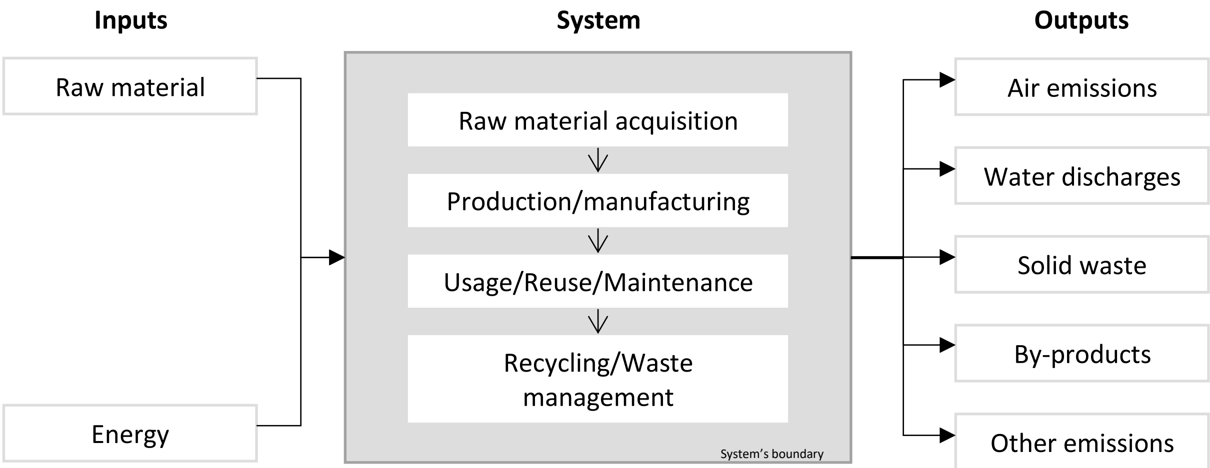

Figure 5 – Inputs and outputs of a system in the context of system-thinking LCA (adapted from ISO 14040, 2006; ISO 14044, 2006 and Ferreira, 2004)

Life Cycle Impact Assessment

Whilst the goal of LCA is to quantify the amounts of energy and materials used and the consequent emissions released into the environment, LCIA is the stage of LCA in which the corresponding impacts of these inputs and outputs are assessed. Methods used for LCIA resort to indicators that are useful to describe the impacts the object of study may have on the environment. Several authors have proposed their own methods to perform this LCA step, making them reliable and verified procedures in terms of assessing environmental sustainability (Ferreira, 2004; Lucas *et al.*, 2014). Regardless of their disparities, most of them follow a general framework, presented in figure 6.

LCIA is made on the assumption that the impacts an object of analysis (*e.g.* a process, a product, or a whole system) prompts can be clustered into impact categories through a midpoint approach, *i.e.*, each midpoint represents an impact category. These impact categories are then associated to an endpoint, which represents a damage category that correlates different impact categories. These endpoints have associated weights that allow, in the end, to compute a single score, enabling direct benchmarking and comparisons (Saur, 1997; Ferreira, 2014). Endpoint methods look at an environmental impact in the end of a given cause-effect chain whereas midpoint methods look at the impact earlier along the same cause-effect chain, *i.e.*, before the endpoint is reached (PRé Sustainability, 2014a). What changes between methods is the number and types of midpoints and endpoints.

What follows is a brief review of the some of the current most relevant LCIA methods (Carvalho *et al.*, 2014; Ferreira, 2004).

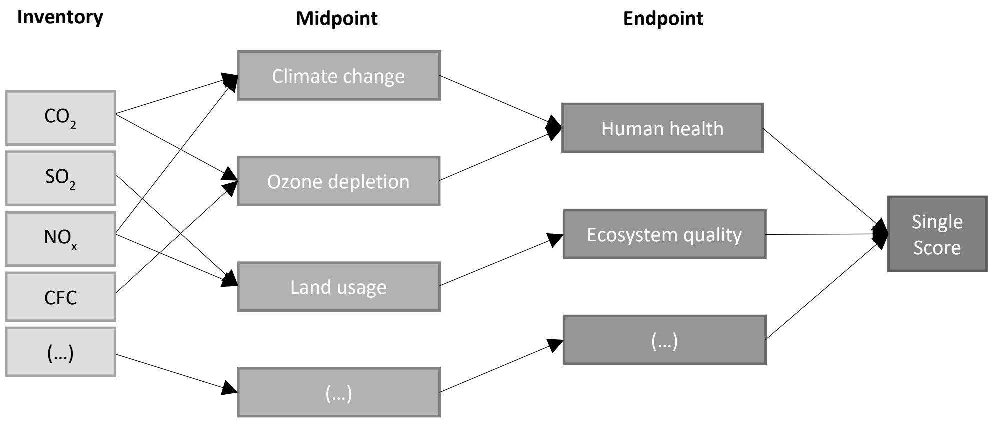

Figure 6 – General LCIA framework (adapted from Lucas et al.*, 2014)*

CML 2002

The CML 2002 LCIA framework was developed by Guinée (2002), from the Dutch *Centrum voor Milieuwetenschappen Leiden* (Centre of Environmental Sciences of the University of Leiden), hence its name. It is a midpoint approach that operationalises the ISO 14040 (2006) standard since it provides recommended normalisation techniques but no weighing methods. Examples of indicators taken into account by this method are, for instance: resource depletion, land usage impacts, loss of biodiversity, human toxicity, eutrophication, noise level, ecotoxicity, among several others (Guinée, 2002; Dias, 2014, Ferreira, 2004; Menoufri, 2011).

Eco-Indicator 99

The purpose of the development of this LCIA method was to simplify the interpretation and weighing phases of the LCA. It was the Eco-Indicator 99 that first implemented the single score approach, allowing it to be directly used into benchmarking and decision-making processes. It adopts an endpoint approach, providing a clear framework for the weighing phase. It evaluates impacts associated to the following three damage categories: human health, quality of ecosystems, and resource usage. For that, it resorts to indicators such as: emissions of carcinogens, climate change, ozone layer depletion, ecotoxicity, land usage, among others (Goedkoop & Spriensma, 2001; Dias, 2014; Menoufri, 2011).

Ecological Scarcity

This LCIA method provides a framework for the weighing stage of several types of emissions, whether on air, soil, water, as well for energy sources. It is, therefore, an endpoint approach. Ecological factors are based on annual flows of materials and energy in a defined area such as a region or a country. This data is gathered from statistical information, provided by different entities from different countries. For this method, the indicators used are: air emissions, ozone layer depletion, emissions to water, emissions to soil, noise, primary energy resources, *etc.* (Dias, 2014; Menoufri, 2011; Brand *et al.*, 1998; Müller-Wenk, 1994).

EPS 2000

The latest version of this endpoint approach method derives from a previous version that was specifically designed for the development of more sustainable products. EPS 2000, which stands for *Environmental Priority Strategies*, was designed to be used together with a Monte Carlo simulation in order to model uncertain environmental mechanisms. It can translate impacts into monetary units and, consequently, into a single score. Some indicators used in this method are: life expectancy, morbidity, crop production capacity, depletion of fossil coal, oil, and gas, among others (Steen, 1999; Dias, 2014; Menoufri, 2011).

Impact 2002+

This LCIA method proposes an implementation of combined midpoint and endpoint approaches, connecting the results obtained in the LCI through fourteen midpoints to four endpoints. All midpoints scores are related to the four endpoints: human health, quality of ecosystems, climate change, and resource usage. Normalisation of scores can be performed in either the midpoint or endpoint stages. Examples of indicators considered in this method are: human toxicity, ozone layer depletion, terrestrial and aquatic ecotoxicity, land occupation, global warming, *etc.* (Jolliet *et al.*, 2003; Dias, 2014; Menoufri, 2011).

ReCiPe

This method is an upgrade of the Eco-Indicator 99 and CML 2002. It harmonises the midpoint and endpoint approaches into a consistent framework. It has sixteen midpoint categories and three endpoint categories. Some indicators present in this method are: climate change, ozone layer depletion, land usage, water shortage, mineral resource depletion, *etc.* (Goedkoop *et al.*, 2008; Dias, 2014; Menoufri, 2011). It is currently the most well-established and comprehensive LCIA method (Carvalho *et al.*, 2014)

3.2.2. Environmental impact categories for industry 4.0

The environmental impacts that are considered in the aforementioned LCIA methods can be clustered into a reduced group of indicators that are likely to acquire particular relevance in assessing the environmental performance of a company with industry 4.0 technologies. These represent a clustering, adapted from the works of Carvalho *et al.* (2014), of suitable impact categories from the ReCiPe and Impact 2002+ LCIA methods in an industry 4.0 context.

Biodiversity

Indicators in this group are useful to assess how much organisations and their activities can put both animal and vegetable species in risk of extinction. The usage of heavy metals, such as lead or other dangerous and toxic substances in their operations can induce infertility on species living in soils, generate inhalable particles, pollute the hydrosphere, and produce volatile organic compounds. Variables like the amount of land occupied by the manufacturing site and the location (*e.g.* proximity to rivers) can affect, either negatively or positively, an environmental indicator (GRI, 2011).

Industry 4.0 technologies are bound to be game changers in this field. The foreseeable constant and real time monitoring of all inputs and outputs of a system, alongside with an optimised use of resources, can be great allies to the reduction of these effluents, improving, therefore, this indicator (Schuh *et al.*, 2014; Wang *et al.*, 2015; Raihanian Mashhadi & Behdad, 2017).

Emission of greenhouse effect gases

Emissions of greenhouse effect gases are, according to the UN (1992), the primary cause of global warming and climate change. As a result, several governmental regulations and international conventions have been developed to contain and control the volume of these gases. Organisations that exceed the limits are, for instance, penalised by sanctions which are, most of the times, monetary (GRI, 2011).

Much like the biodiversity group, industry 4.0 is bound to reduce the volume of greenhouse effect gases by optimising the amount of raw materials used and streamline processes (Schuh *et al.*, 2014; Wang *et al.*, 2015; Raihanian Mashhadi & Behdad, 2017).

Human Health

This impact category assesses the damages to the health of human beings that are caused by emissions of fine particles, ozone, smells, or even the level of noise generated by a process. Fine particles with a diameter inferior to 10 µm, for instance, represent a complex mix of organic and inorganic compounds. These particles affect the health of humans by reaching the respiratory tract when inhaled. Additionally, secondary aerosols are formed in the atmosphere from sulphur dioxide, ammonia, nitrogen oxides, *etc.*. High concentrations of these particles and substances can inflame the trachea and/or the lungs and may lead to chronic diseases such as asthma (GRI, 2011; WHO, 2003).

Toxicity

This impact category entails ecotoxicity and human toxicity. Human toxicity focuses on the effects of the direct exposure to chemicals and the consequent effects on a human being's health. Unlike the human health impact category, toxicity assesses, for instance, the effects of carcinogens. Ecotoxicity, on the other hand, focuses on the effects chemical substances have on non-human organisms. It assesses the exposure living beings have regarding toxins in their ecosystems (GRI, 2011; Dias 2014).

Water and energy consumption

The volume of water withdrawn from nature is an indicator of the potential impacts and risks an organisation may have with their water usage, as it takes into account, precisely, the amount of water used in the organisation's operations (GRI, 2011).

In order to fight climate change and global warming, making the shift from fossil fuels to renewable energies as a source of energy is essential. Renewable energy technologies imply minoring impacts on the extraction and processing of energy phases, but also a loss of dependency on the prices of raw forms of non-renewable energy, allowing organisations to become more resilient to the volatility of the markets (GRI, 2011). This indicator measures the consumption of primary energy of the object of analysis, separating it by provenience, *i.e.*, if it comes from renewable or non-renewable sources. The environmental footprint of an organisation can be, therefore, measured by the energy mix it resorts to. There is also a correlation between this indicator and the greenhouse gases emission one: the higher the use of fossil fuels as primary energy source, the higher the volume of greenhouse gasses that are emitted (GRI, 2011).

Generated waste

This impact category assesses data regarding the amount of both energy and materials that were wasted in the course of several years of activity. Kemna *et al.* (2005) argue that the amount of waste that goes to landfill and the one that goes to incineration without energy recovery provide significant information regarding how much an organisation wastes. This data can also be used to track the effort a company has been doing regarding waste management and reduction. A decrease in waste will have a direct impact in the company's bottom line, since it is directed to the costs of operation, *i.e.*, the less materials used, the less money spent.

Once again, the shift to industry 4.0 is certain to reduce the generation of waste by allocating the optimal quantity of materials and energy to the corresponding processes (Schuh *et al.*, 2014; Wang *et al.*, 2015).

3.3. Social dimension

Social sustainability is about fulfilling the needs of people and society overall. It encompasses topics such as health and safety standards and regulations, the topic of human-centred design of work (ergonomics), the empowerment of individuals, namely stakeholders, work-life balance, among several other aspects wherever there is a linkage between an organisation and its stakeholders (Gregori, 2017). Vallance *et al.* (2011) argue that social sustainability is composed of three layers, distinguishing tangible and non-tangible social needs: the developmental layer addresses the topics of poverty and inequality in societies, the bridging layer is about setting strategies that will influence both the social and the environmental dimensions of sustainability, and the maintenance layer is related to the protection of existing socio-cultural characteristics. Policies that aim to improve an organisation's social sustainability ought to find the right balance between these three layers.

Another concept that is intimately related to social sustainability is Corporate Social Responsibility (CSR). CSR is defined, according to the European Commission (2011), as the responsibilities a given organisation has for the impacts they may cause in society. It is also an umbrella term for the social and environmental concerns a business has in its operations and its voluntary interactions with stakeholders. The topics of CSR and the social dimension of sustainability are, therefore, intimately intertwined (Ashby *et al.*, 2012). The European Commission (2011) also argues that there is evidence to sustain that organisations that commit in employing successful CSR policies benefit directly from it economically by creating a better work environment that, in its turn, translates into higher levels of productivity. Additionally, commitment to CSR is also translatable into a more efficient use of natural resources, which decreases the generation of waste and the environmental footprint of the company. This commitment to social and environmental standards is also a form of market currency, which enables the organisation to enhance its reputation and create new market opportunities. Overall, compliance and commitment to CSR regulations bring value to the company (European Commission, 2011; Melro, 2018). There are, however, some downsides of considering the implementation of CSR programmes as direct indicators of social sustainability. Smaller organisations, for instance, that tend to have lower resources available, may struggle to implement CSR programmes due to the initial investments required, which poses as a barrier to their implementation (Ciliberti *et al*., 2008). CSR is also complex to hypothesise and use in a pragmatic context due to the differences between markets in terms of needs, cultures, creeds, *etc.*, making it unable to create standardised and *one-fits-all* CSR programmes (Simões, 2014).

What follows is an exposition of commonly used (GRI, 2011; Simões, 2014) methodologies, tools, and indicators to assess an organisation's social sustainability practices, namely SLCA, stakeholder analysis and management, and ergonomics.

3.3.1. Social Life Cycle Assessment

Social Life Cycle Assessment (SLCA) is a methodology that, much like the aforementioned LCA, evaluates both positive and negative impacts – regarding the social dimension – an object of study (*e.g.* product, process, system, *etc.*) prompts throughout its life cycle. Its overall goal is to promote wellbeing and positive social conditions which will, ultimately, interfere with the economic and environmental dimensions (Simões, 2014; Cadena *et al.*, 2018). SLCA therefore addresses the problem of measuring positive and negative social impacts whilst producing information in which decision-making processes can be supported at the same time it brings the topic of social sustainability to the table (Fontes *et al.*, 2018; Cadena *et al*, 2018).

SLCA follows the same generic framework as LCA, depicted in figure 4. However, SLCA tends to be more complex than LCA due to that fact that it assesses, in a quantitative manner, intangible attributes such as, for instance, stakeholder's wellbeing (Benoît *et* al., 2010; UNEP SETAC, 2009). SLCA handles semi-qualitative and qualitative data, which is not necessarily linked to process throughput, so the definition of a functional unit is not as crucial as in LCA. The reason is that these methods are linked to social impacts through proxies (*e.g.* working hours, monetary values or a combination of both) (Sala *et al.*, 2015; UNEP SETAC, 2009; Cadena *et al*, 2018). Nonetheless, SLCA is designed to be applied either solely or as a complement to LCA (UNEP SETAC, 2009).

Two other blurry issues of SLCA arise upon application. One is regarding the allocation of impacts, in which some authors argue they should be directly indexed to the products through a weighing process while others say that the manufacturing process should be assessed as a whole (Benoît *et al.*, 2010; Simões, 2014). The other is regarding the definition of the boundary of the system and the inventory phase, in which, depending of the chosen system frontier, the amount of required data to apply SLCA may be too high and, therefore, unfeasible to obtain (Benoît *et al.*, 2010; UNEP SETAC, 2009; Simões, 2014).

In the impact assessment phase, the UNEP SETAC (2009) argues that the types of impact categories assessed should be dependent on the goal and the scope of the study and on stakeholders' interest. Examples of impact categories are: human rights compliance, health and safety regulations compliance, working conditions, cultural heritage, *etc.*.

Whilst arguing that SLCA needs a more comprehensive approach and clear and unequivocal methodologies, Cadena *et al.* (2018) have developed their own five-step methodology that, despite being designed to be applied in early stages of process design evaluations in industrial projects, can be extrapolated to subsequent phases. It is also compliant with the methodologies proposed by UNEP SETAC (2009).

The first step is to define the goal of the study. It should be clear, specific, and unequivocally stated what is the object of analysis and the expected outputs of the application of the methodology. Additionally, the life cycle of the object of study should be defined, as well as the boundary of the system. Relevant stakeholders should be included in this discussion. Step number two refers to the phase in which the data collection has to be performed. Despite the use of real data, which could be collected via the stakeholders of the system, being the one that would return the most accurate results, the authors advise to collect the required data from indirect sources such as literature reviews, reports, or even search engines due to the complexity of this task. The third step is where the identification, assessment, and classification of stakeholders affected by the project is made so that an involvement plan is elaborated. It begins with elaborating a list, iteratively, with the stakeholders that might affect or be affected by the problem in discussion, *i.e.*, the potential most important stakeholders. Then, they should be classified according to their power, interest, and/or supportiveness. Finally, the stakeholder's requirements should be identified, and the impacts should be, accordingly, performed. It is expected that, in the end, stakeholder's activities are reported, and the respective mechanisms of interaction are presented. The fourth step refers to the selection of appropriate indicators that assess the social impact of the project's activities. First, social indicators ought to be matched with stakeholders via cause-effect relations. In this case, a linkage is made between sixteen midpoints and four endpoints (labour practices and decent work, society, product responsibility, and human rights). Then, an identification of the system's hotspots, *i.e.*, the most critical indicators, by means of performance reference points, is performed. This is also the step in which the selection of the most appropriate indicators ought to be made according to the scope of the case-study in discussion. In the fifth and final step, the interpretation of the applied SLCA is made. Here, guidelines for improvements ought to be proposed, hotspots should be identified, and a plan defining the future course of action is to be designed.

It matters to say that SLCA methodologies might suffer some disruptions when applied to the industry 4.0 and smart manufacturing contexts. Gregori (2017) proposes an SLCA method that implies that, in the data collection phase, the IoT structure of a plant, alongside with the CPS, will be responsible for a real time collection of data. This is an extension of the works carried out by Raihanian Mashhadi & Behdad (2017) for standard LCA.

3.3.2. Stakeholder analysis and management

An accurate analysis, evaluation, and categorisation of all stakeholders that are bound to affect or be affected by a given project or any other disruption is essential to evaluate and assess social sustainability, as argued by Cadena *et al.* (2018). Freeman (2010) defines a stakeholder as any group or individual that can either affect or be affected by whatever actions that arise from the attainment of goals and objectives by a given organisation. Eden & Ackermann (1998), on the other hand, define them as individuals or small groups that hold the power to respond to, negotiate with, and change the strategic future of the organisation. Therefore, when performing any type of social assessment, the collection of insights regarding stakeholders is crucial.

Several stakeholder identification methodologies have been developed in academia. Bryson (2004) developed the Basic Stakeholder Analysis, which quickly assesses stakeholders' sentiment regarding the object of analysis (*e.g.* a project). It lists all their expectations and assigns them a traffic light classification (red, yellow, or green) according to the stakeholder's feeling on the project's status in face of her/his expectations. The outcoming table can also contain indications on how to quickly please each stakeholder and long-term issues they may have. The overall purpose of this methodology is to assess the project's health at the end of a milestone and to identify which stakeholders are at stake at a given point in time. Reed *et al.* (2009), in its turn, proposed the Snowball Sampling methodology, which can be used simultaneously with the previous. It consists in interviewing stakeholders from initial categories, *i.e.*, the ones that were identified with the Basic Stakeholder Analysis, for instance, so that they themselves identify other possible stakeholders, allowing to extend the analysis. Hart & Sharma (2004) developed, on the other hand, the Radical Transactiveness methodology. It analyses the traditional (core) stakeholders' points of view whilst integrating the ones coming from more peripherical (fringe) stakeholders. It has the advantage of identifying a greater range of stakeholders, some of which would not even be considered in the other two aforementioned methodologies, but can unnecessarily overwhelm the analysis, making it slower and more complex.

Following the identification of the stakeholders, they ought to be categorised. The power-interest matrix, presented by Ackermann & Eden (2011) and depicted in figure 7, is one way of achieving it. This framework is based on categorising the previously identified stakeholders according to the power they hold, *i.e.*, the likelihood of a stakeholder acting according to his own will despite external resistance, and their interest, *i.e.*, the responsibility, feeling of involvement, and concern the stakeholder has regarding the a given project, for instance. Stakeholders are then, accordingly, compartmentalised into the following four categories:

- **Subjects** – These stakeholders should always be kept informed so that no problems arise, meaning that communication is crucial;
- **Players** – Stakeholders that should be totally involved in the processes and an effort should be made to keep them satisfied. They should then be kept informed and satisfied at all times;
- **Crowd** – Should be monitored, but an excessive amount of time and resources should not be allocated;
- **Context Setters** – Should be kept satisfied and informed, but only with the essential information due to the lack of interest.

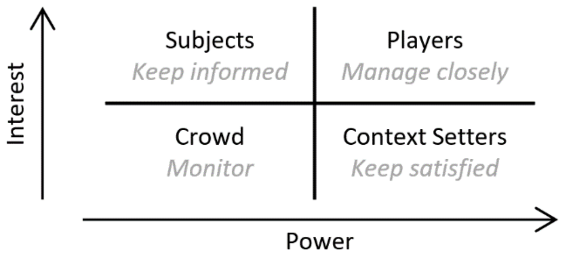

Figure 7 – Power-interest matrix (adapted from Ackermann & Eden, 2011)

Another stakeholder categorisation methodology that can be important when handling the topic of the introduction of industry 4.0 technologies on the shop floor level is the problem-frame matrix, proposed by Nutt & Backoff (1993) and depicted in figure 8. Its goals are to determine which stakeholders are likely to support or be opposed to a specific recommendation. Analogously to the power-interest matrix, it graphically represents where stakeholders should be positioned in terms of their supportiveness.

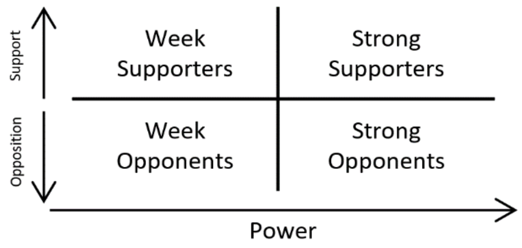

Figure 8 – Problem-frame matrix (adapted from Nutt & Backoff, 1993)

One additional step that ought to be made when performing a stakeholder analysis is the evaluation of the possible existing relations between stakeholders. For that, some methodologies are available. Reed *et al.* (2009) proposed a very straightforward approach that simply lists all stakeholders by row and column, stating the type of relationship that exists among them. Despite its straightforwardness, the excessive simplification may hinder important details that should be considered, compromising subsequent assessments. Bryson (2004), in its turn, designed a different type of matrix that lists stakeholders by row and the interactions (*e.g.* inform, consult, involve, *etc.*) that ought to be made with them by column. This provides a visual piece of information that can, however, be difficult to materialise when handling complex relationships. Cameron *et al.* (2008) argue that, for a more thorough assessment of the existing linkages between stakeholders, a value flow map ought to be sketched. This methodology identifies, clusters, and maps the complex relationships between stakeholders taking into account the value they have in terms of problem-solving. The outcome is a flowchart that highlights the linkages between stakeholders.

To complement the abovementioned methodologies, an effort should be made to understand the risks associated to managing stakeholders. Here is where the concepts of risk analysis and management enter the discussion. The Project Management Institute (PMI) argues that these practices ensure that the number of surprises that may occur is minimised whilst a given project is ongoing (Lavanya & Malarvizhi, 2008). The PMI proposes a four-step framework that allows to assess and manage risks, outlining that effective and early risk identification and management procedures secure the achievement of a given project's objectives.

The first step is to identify the risks. Risks are to be identified and dealt with as early as possible in the project. This identification can be performed throughout the project life cycle with special emphasis in key project milestones. This identification can be performed taking into account historical data from similar projects that have already been completed, organise project status meeting reports so that insights into the potential new risks that may arise are duly registered, or even by interviewing experienced stakeholders. The identified risks should then be categorised according to the business areas that risk may cause disruptions to (*e.g.* logistics, technology, quality, *etc.*). The second step is the analysis of the risk itself. It involves examining how project outcomes and objectives might change due to the impact of the risk event. Once identified, the risks are analysed to identify the qualitative and quantitative impacts on the project so that appropriate steps can be taken to mitigate them. To prioritise them, a score should be attributed to each risk. Table 2 presents the guidelines for this step. It takes into account the probability of occurrence, p, and its impact, segmented into three magnitudes: high, medium, and low, to which were attributed semi-quantitative impact scores of 100, 50, and 10, respectively. The scores, computed by multiplying the impact scores with the upper bound of the probability value, is presented between parentheses. The expected timeframe for a given risk to have an impact should also be stated. Following the assessment of the risks, the third step is about designing response plans for each of the identified risks. A risk response plan aims to either eliminate the risk, to lower the probability of occurrence, or to lower its impact. Additionally, risk triggers should be documented. The trigger identifies the risk symptoms and/or warning signs and indicates that a risk has occurred or is about to occur. It also gives an indication of whether a certain risk is expected to occur in the near future. Lastly, the respective risk owners should be determined. A risk owner is the one who can best monitor the risk trigger and can best determine respective countermeasures. Finally, the last step is the monitoring and controlling of the risk. It entails the identification of new risks, the tracking, monitoring, reclassification of the existing risks, and its respective reporting.

Table 2 – PMI guidelines for risk assessment (Lavanya & Malarvizhi, 2008)

		Probability of occurrence, *p*			
		High $0,8 \le p \le 1$	Medium high $0,6 \le p < 0,8$	Medium low $0,3 \le p < 0,6$	Low $0 \le p < 0,3$
Impact	High (100)	Very High Exposure (100)	Very High Exposure (80)	High Exposure (60)	Moderate Exposure (30)
	Medium (50)	High Exposure (50)	Moderate Exposure (40)	Moderate Exposure (30)	Low Exposure (15)
	Low (10)	Low Exposure (10)	Low Exposure (8)	Low Exposure (6)	Low Exposure (3)

3.3.3. Social sustainability and industry 4.0

Industry 4.0 promises to bring new technologies onto the shop floor level and to change the way employees and machines interact (FCT, 2018; Cherubini *et al.*, 2016). With that, a rethinking of the human-centred design of work for the smart manufacturing age ought to be performed. Ergonomics enters here in the discussion as the process of designing products, systems, or setting layouts for workplaces so that they fit the ones who use them. The basic concepts of ergonomics are defined in the ISO 26800:2011 series (Gregori, 2017). This last author argues that ergonomics is a multiple factor concept that entails physical, cognitive, environmental, and organisational dimensions.

Physical ergonomics is related to the relationship between anthropometric, physiological, biomechanical characteristics, and the dynamic and static parameters of physical effort at work (Sherehiy & Karwowski, 2006). It is the most visible dimension of ergonomics as it handles safety and health factors such as working postures, handling of materials, and work-related musculoskeletal disorders. Driscoll *et al.* (2014) state that musculoskeletal diseases pose an economic burden for organisations since they represent the main cause of absenteeism. Gregori (2017), apart from the musculoskeletal diseases and absenteeism rates, argues that indicators such as heart rates, breath rate, and oxygen consumption can be considered valid indicators to measure comfortability at work and risk of physical overload.

The concept of cognitive engineering arises from the works of Norman (1987) and is related to the awareness, attention, motor response, perception, memory, and ability to make decisions in a work context. It mainly focuses on mental stress, *i.e.*, the effect of all environmental factors in an operator's cognitive and emotional capabilities, and assesses the correlation between workload, probability of errors, and its consequences (Norman, 1987). Gregori (2017) argues that the introduction of industry 4.0 technologies on the shop floor level will increase the complexity of the information a worker has to acquire and process, which may potentialize the increase of mental workload and the probability of errors. Cognitive ergonomics can be assessed through, for instance, surveying employees to self-assess their perception towards a given task or even through psychophysiological data such as heart rate, pupil dilatation, and brain activity (Norman, 1987; Gregori, 2017).

Environmental ergonomics is related to the workplace environment, *i.e.*, the surroundings where employees spend a given number of hours per day. Elements such as the level of noise, indoor air quality, intensity of light, and/or thermal amplitudes may trigger psychophysiological responses such as mood swings and headaches which influence both the quality of life of the workers and the quality of the production itself (Jokl, 1982). This is the dimension of ergonomics for which there are clear indicators, making it the most straightforward to assess. For instance, noise can be easily measured in dB, indoor air quality by parameters such as CO, CO_2, particle levels, *etc.* (Gregori, 2017).

Lastly, organisational ergonomics relates to the configuration of the organisation itself and how the workload is distributed across the workforce. It concerns the optimisation of work systems, including organisational processes, structures, and policies (Gregori, 2017).

Compliance with ergonomics standards is, thus, one set of indicators to assess social sustainability in organisations and one that acquires higher importance in the age of smart manufacturing. Simões (2014) additionally provides a listing of other social indicators. Table 3 summarises some of these indicators that may be suitable to assess social sustainability within the industry 4.0 context due to their applicability to manufacturing industries.

Table 3 – Social indicators found in the literature (based on Simões, 2014)

GRI social category	Examples of indicators
Labour practices and decent work	〉 Fatalities per employee; 〉 Fatalities caused by large accidents; 〉 Frequency of accidents; 〉 Employee turnover; 〉 Fraction of hours of training relative to total hours worked.
Society	〉 Support to neighbouring educational institutions; 〉 Engagement in public and cultural activities; 〉 Level of acceptance by local community; 〉 Involvement of stakeholders in the organisation's operations.
Human rights	〉 Freedom of association between employees (formation of unions); 〉 Right to organise; 〉 Compliance to laws/regulations regarding child labour.
Product responsibility	〉 Number of customer complaints and claims; 〉 Product reliability and use of ecolabels. 〉 Amount of potentially imported fossil fuel avoided.

Industry 4.0 technologies will, therefore, allow for more accurate and updated sustainability metrics to be retrieved, allowing organisations to have palpable data for which to work with and act upon, placing, finally, sustainability on the decision-making table.

3.4. Overview of research on sustainability and industry 4.0

Despite the increasing awareness regarding industry 4.0 and its technologies from both academia and enterprises, there is yet an insufficient amount of literature and research on the topic itself, let alone on sustainability within industry 4.0. However, throughout the years, yearly publications on the topic have been growing at an almost exponential rate, as figure 9 shows (Kamble *et al.*, 2018). Another fact worth mentioning is that the USA, the UK, and the Netherlands make up the top 3 countries where these papers are originally published (Kamble *et al.*, 2018; Lu *et al.*, 2016). As to the level and extent of research within the topic of industry 4.0, table 4 summarises which fields and which approaches are usually addressed in research, as well as their frequency (Kamble *et al.*, 2018). The fields of human-machine interaction and sustainability in industry 4.0 are, as shown in table 4, the most disregarded topics. It is also worth mentioning that around 29% of studies on human-machine interactions and 33% of the ones on sustainability use a case study methodology to conduct their researches. Kamble *et al.* (2018) also state that, whilst recognising the potential industry 4.0 may have on value creation in the social dimension, most existing literature on sustainable industry 4.0 focuses on the economic and environmental dimensions. This contrasts with Stock & Seligar (2016) when they argue that industry 4.0 is the enabler of a turning point that will bring sustainability into the creation of industrial value.

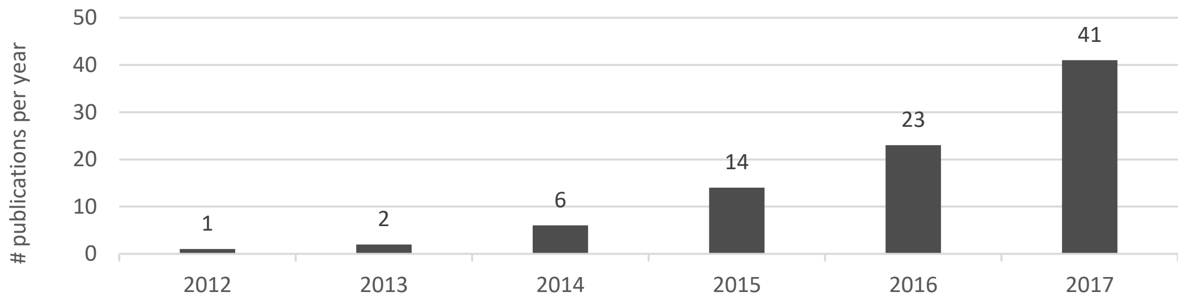

Figure 9 – Yearly publications on industry 4.0 (Kamble et al.*, 2018)*

As to what the economic dimension is concerned, the literature points out that industry 4.0 technologies will enable a reduction in manufacturing costs since production will become much more traceable in real time, allowing to integrate lean manufacturing philosophies that provide much more consistency to the process. Another big advantage of industry 4.0 in the economic side is that the costs of implementing these technologies can be further reduced since they can be run by third parties thanks to cloud-based computing, freeing organisations from that burden (Ramadan *et al.*, 2017; Lao *et al.*, 2015). However, the current investment barrier is still high and may be out of reach to small and medium enterprises (SMEs) (FCT, 2018).

Table 4 – Level and extent of research on industry 4.0 topics (Kamble et al.*, 2018)*

Research category	Conceptual	Case study	Simulation	Experimentation	Survey	Prototype	Total Papers
Key technologies	23	19	7	5	1	2	**57**
Shop floor-Equipment interactions	15	11	5	5	0	1	**37**
Concepts and technologies	30	0	0	0	0	0	**30**
Human-Machine interactions	7	6	2	1	3	2	**21**
Sustainability	6	5	3	0	1	0	**15**

In the environmental dimension, industry 4.0 will expectedly allow factories to become, thanks to the real time collection of data, much greener since it will be possible to allocate resources much more efficiently at the same time it reduces the production of waste and avoids possible overproduction. However, in the other side of the picture, the necessary equipment and technological infrastructure in which industry 4.0 is based require higher levels of energy and resource consumption to operate, which has a negative impact on the environment (Schuh *et al.*, 2014; Wang *et al.*, 2015).

Despite being the number one methodology to assess the environmental impacts of a product or service (European Commission, 2016; ASMI, 2018), standard LCA may have some limitations when applied in the field of smart manufacturing and industry 4.0 (Raihanian Mashhadi & Behdad, 2017). These authors list the following reasons to justify this unsuitability:

- Inability to address emerging systems;
    - LCA requires well-established data to assess the impacts of the object of analysis. In the context of industry 4.0, LCA may not be yet capable of correctly evaluating the impacts of some operations and processes since the existing databases do not yet hold information to cover emerging technologies and behaviours (Reap *et al.*, 2008; Alfaro *et al.*, 2010);
- Limitation to steady-state systems;
    - LCA focuses on global perspectives whilst assuming increased levels of homogeneity between variables and systems. Therefore, it may not offer accurate results when applied to systems where temporal and spatial effects are part of the equation (Haes *et al.*, 2004).

These limitations may hinder the use of standard LCA to accurately assess the possible environmental impacts of smart manufacturing topics in the midst of the shift to industry 4.0. However, these exact changes provide new capabilities to LCA. The inherent self-awareness smart products and processes using industry 4.0 technologies possess can be used to provide real time and accurate data regarding the inputs and outputs of a system, *i.e.*, each machine or process can be equipped with an interconnected environmental tracker that tracks and reports inputs and outputs in real time. In order to overcome these limitations, these last authors define the Ubiquitous Life Cycle Analysis as an LCA method that uses industry 4.0 technologies, like RFID and IoT, to allow the collection in real time of the necessary data for the application of this methodology throughout the whole product life cycle. Using the recorded environmental impacts data, combined with deep learning and multi-objective optimisation techniques, optimum configurations that simultaneously meet economic, environmental, and even social requirements are achievable (Raihanian Mashhadi & Behdad, 2017).

Whilst being the most disregarded, the social dimension of sustainability has been lightly covered in the literature. Several authors have stated that, whilst the speedy industrialisation has been a cause for low standards of living and source of strains in the environment, industry 4.0 is set to use modern technologies to help recover from this exact deterioration in environmental and social values (Stock and Seligar, 2016; Luthra & Mangla, 2018; Oesterreich & Teuteberg, 2016). In their work, Stock and Seligar (2016) have proposed three approaches to handle the social challenges that industry 4.0 carries:

- Increase and promote training on ICT for workers;
- Promote motivation, creativity, and gamification to support decentralised decision-making;
- Use performance feedback mechanisms to implement individual incentive schemes.

In conclusion, the attention given to the topic of sustainability in industry 4.0 in the literature has been very limited and merely focused on the economic and environmental dimensions (Kamble *et al.*, 2018). One of the aims of this work is, precisely, to reduce the literature gap in the field of sustainability within industry 4.0.

3.5. Chapter conclusions

The present chapter dove into finding appropriate and suitable sustainability metrics and indicators for the topics of industry 4.0, in each of its three dimensions. Table 5 therefore aims to systematise all that has been discussed by presenting a list of methodologies and indicator sets whose relevance in any assessment of sustainability in an industry 4.0 context has proven to be undeniable.

Table 5 – Suitable sustainability metrics, tools, and indicator sets for industry 4.0 (source: author)

<table>
<tr><td rowspan="1">Economic dimension</td><td colspan="2">〉Direct and indirect economic impacts (GRI, 2011; IChemE, n.d.);
〉Financial implications of climate change (GRI, 2011);
〉Investment analysis and profitability (IChemE, n.d.; Weber et al., 2008);
〉Level of financial autonomy (GRI, 2011);
〉Productivity and quality (GRI, 2011; IChemE, n.d.; Bleischwitz et al., 2009);
〉Proportion of expenditure on local communities and enterprises (GRI, 2011).</td></tr>
<tr><td rowspan="2">Environmental dimension</td><td>Methodologies</td><td>Impact categories</td></tr>
<tr><td>〉Life Cycle Assessment (European Commission, 2016; ASMI, 2018);
〉Ubiquitous Life Cycle Assessment (Raihanian Mashhadi & Behdad, 2017).</td><td>〉Biodiversity (GRI, 2011);
〉Emission of greenhouse effect gases (GRI, 2011);
〉Energy consumption (GRI, 2011);
〉Generation of waste (Kemna et al., 2005);
〉Human health (GRI, 2011; WHO, 2003);
〉Toxicity (GRI, 2011);
〉Water consumption (GRI, 2011).</td></tr>
<tr><td rowspan="2">Social dimension</td><td>Methodologies</td><td>Indicator sets</td></tr>
<tr><td>〉CSR policies (Ashby et al., 2012; European Commission, 2011);
〉Social Life Cycle Assessment (Cadena et al., 2018; Benoît et al., 2010; UNEP SETAC, 2009);
〉Stakeholder analysis and management (Cadena et al., 2018; Lavanya & Malarvizhi, 2008).</td><td>〉Ergonomics (Gregori, 2017; Sherehiy & Karwowski, 2006; Driscoll et al., 2014; Norman, 1987);
〉Human rights (GRI, 2011; Simões, 2014);
〉Labour practices and decent work (GRI, 2011; Simões, 2014);
〉Product responsibility (GRI, 2011; Simões, 2014);
〉Society (GRI, 2011; Simões, 2014).</td></tr>
</table>

4. Methodology for the development of Sustainability 4.0

This chapter outlines the methodology for the development of Sustainability 4.0. It takes into account both the research gaps that were found upon the literature review and the research question defined in the first chapter. It additionally defines and clarifies the steps for the development of such a tool, providing a clear theoretical and scientific sustenance for each step.

Given the problem at stake, namely the need to find a way to accurately, quantitively, and comprehensively assess the impacts of the introduction of industry 4.0 technologies on the shop floor level in terms of the three dimensions of sustainability, a generic tool to assess sustainability in a comprehensive manner, as well as to assist and support decision-making processes in a smart manufacturing context, is to be developed.

The intended outputting tool – **Sustainability 4.0** – is hereby developed to assess, by means of indicators and KPIs, sustainability issues in either of the following two contexts:

- **Context A** – Following the introduction of industry 4.0 technologies on the shop floor level, in case the application of this tool is being performed after that moment, analysing the impacts and changes it prompted;
- **Context B** – During that technological shift, in case the application of this tool is being performed in any given point in time from the start to the end of the implementation phase, highlighting possible gaps between current situations and target ones.

Therefore, this work proposes the creation of an instrument to be applied in cases where the shift to industry 4.0 either already took place or is scheduled to be made. The goal is that sustainability aspects can be assessed with this instrument and decision-makers (or policymakers, when applicable) can act upon any detrimental changes or insufficiently met KPIs resultant from the implementation of industry 4.0 technologies with the development of a stakeholder engagement plan. This tool must also be suitable to be used in any given case regardless of the industry or sector it is being applied to. This is one of the reasons that justifies the cruciality of developing and presenting a generic version of this tool at the outset.

The methodology of work – which yields the desired outputs – comprises four steps, as depicted in figure 10, in which the first three correspond to the development of Sustainability 4.0 *per se* and an additional one corresponds to the development of a stakeholder engagement plan. Overall, similar guidelines followed by the aforementioned works of Cadena *et al.* (2018), namely an extension of their methodology to carry out an SLCA to the other two dimensions of sustainability, were taken into account. Each step is further described below.

The output of the first step of this methodology is the definition of the scope of the assessment, as well as a description of the system under analysis. Here, the goals of the study, as well as its expected outputs, should be clearly and unequivocally stated and specified. The life cycle of the object under assessment (*e.g.* product, service, process, *etc.*) and the boundaries of the study, if applicable, should also be defined by adopting a systems-thinking philosophy that highlights the interconnections between the three dimensions of sustainability. To accomplish this, the technique carried out by the aforementioned works of Cato (2009), schematised in figure

3, is suggested and will be used in this work. The execution of this step should include, whenever possible, the contribution of the most relevant stakeholders so as to guarantee the comprehensiveness of the assessment.

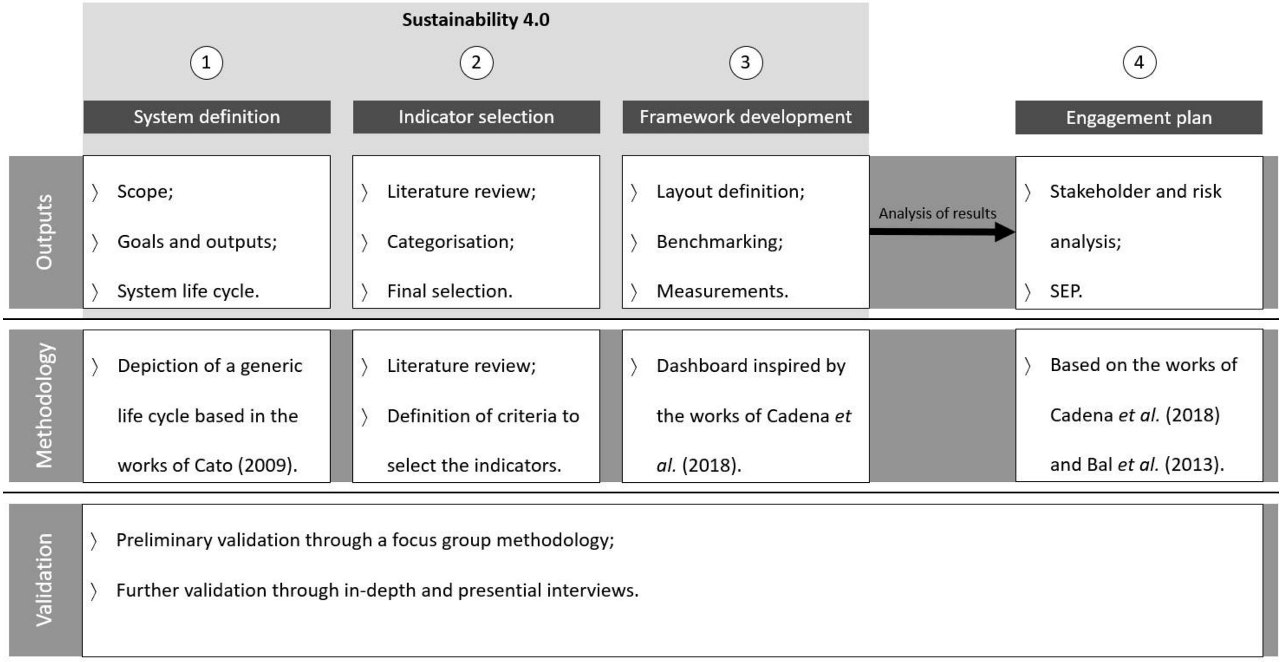

Figure 10 – Methodology for the development of Sustainability 4.0 and the SEP (source: author)

The second step of this methodology is about selecting suitable sustainability indicators to be included in such an assessment. This can be accomplished by means of state-of-the-art and literature reviews. In this work, the literature review was performed through the analysis of scientific papers available in online publishers such as Elsevier, Science Direct, GRI, IChemE, *etc.*, in which some of the keywords used for the search process were "social sustainability", "economic sustainability", "environmental sustainability", "sustainability assessment", "sustainability + smart manufacturing", and "sustainability + industry 4.0". Likewise, more indicators were also retrieved through the analysis of other non-scientific documents such as sustainability and other organisational reports found through search engines resorting to similar keywords. The results of this analysis were presented in the previous chapter. Moreover, if a generic tool that serves the purpose of assessing sustainability in an industry 4.0 context is to be developed, meaning that it can be used in any organisation regardless of the industry it operates in, whilst there can be no *one-fits-all* indicator list, a criteria for the selection of indicators to be included in such an assessment ought to be defined. Therefore, this step should yield the final selection of the indicators that are to be present in such an assessment.

The third step is to develop the general framework of Sustainability 4.0. Following the selection of indicators that are to be present in the assessment, the end user should decide how the results are going to be presented. Inspired by the works of Cadena *et al.* (2018), a model for a dashboard, extended to the three dimensions of sustainability, essentially made up of columns and rows, was developed. The dashboard should present information regarding one indicator for each of the rows that compose it so that the end user can easily interpret it and act upon accordingly. This can be materialised in whichever medium the end user finds best to work with.

Following the analysis of results provided by the dashboard of Sustainability 4.0, namely the identification of hotspots, the fourth stage is the development of an SEP to mitigate (or even eliminate, whenever possible) these exact hotspots. A planned, well-defined, and successful engagement of stakeholders involves getting their support and develop collaborative tools to devise, plan, and develop new business solutions (Persson & Olander, 2004). In this work, the proposed SEP development methodology is a hybrid between the works of Cadena *et al.* (2018) and Bal *et al.* (2013), meaning that the methodology proposed by the first group of authors is used and the linkage to sustainability objectives proposed by the second group of authors is added.

In order to validate both the scientific validity and the real-life applicability of Sustainability 4.0, a two-stage process took place. Firstly, the tool was discussed and validated through a focus groups with experts in the field. A focus group is a consolidated research methodology that takes the form of a well-structured discussion that involves progressive sharing of ideas and clarification of points of view by all participants. Focus groups can be conceptualised as a group interviews, mediated by a facilitator, providing researchers the ability to capture meaningful information in a more efficient way comparing to the conduction of individual interviews. For this reason, it is used in academia to generate knowledge and information, test innovative measures, or to clarify the goals and scope of a given project, for instance. This methodology can be integrated into an overall study design or can occur individually when a specific topic is being explored, which was the case for this work (Greenbaum, 1998; Ritchie & Lewis, 2003). Then, following the experts' approval of the presented version of Sustainability 4.0 upon the conduction of the focus group, the validation methodology that was used to further validate the tool consisted in the conduction of face-to-face (whenever possible) in-depth interviews with experts in the field, *i.e.*, more specifically, renowned academics from two European universities, as well as individuals whose expertise and knowledge in the topic of industry 4.0 within the Portuguese industrial fabric and governmental agencies is widely acknowledged. This is essential to collect and analyse feedback from both a theoretical, and a more hands-on and pragmatic perspectives on both the validity and applicability of the developed tool.

The conduction of face-to-face (or through videoconferences), one-on-one, and verbal in-depth interviews allows to test, validate, and collect feedback in a comprehensive fashion regarding the validity of Sustainability 4.0 and its applicability to a real-life context. This methodology has gained popularity among academics due to its effectiveness in collecting and verifying information (Fontana & Frey, 2000). For this case in particular, the main goals of the conduction of these in-depth interviews was to:

- Assess interviewees' perception of the way and extent industry 4.0 will impact an organisation in terms of sustainability;
- Evaluate if Sustainability 4.0 will, effectively, assist decision-makers in making more sustainable decisions;
- Assess whether or not the application of Sustainability 4.0 to a real-life context is feasible;
- Know how the interconnectivity and real time measurements, which are some of the premises of industry 4.0, enables Sustainability 4.0 to become a tool that could be used to assess sustainability issues in real time;
- Collect feedback on how can Sustainability 4.0 be further improved.

Prior to the conduction of the interviews, an interview script was developed, building the basis for the conduction of a semi-structured interview. This type of interview consists in enquiring interviewees with the previously scripted questions and adding hypothesis-directed, more technical, and probing ones on several other predetermined topics chosen by the interviewer whenever deemed appropriate and/or necessary (Flick, 2006). The decision to carry out semi-structured interviews was made so as to allow interviewees to answer to the questions based on both their explicit and implicit presumptions and knowledge, whether from a theoretical or a more empirical and based on expertise background. This allows to collect information about the interviewees' own opinions and thoughts about the discussed topics, as well as to validate the developed tool from the applicability standpoint (Flick, 2006). To develop an interview script, questions must be thought through prior to the conduction of the interviews. These can be of three types:

- **Open questions** – Are made in an attempt to capture the interviewees' knowledge, perceptions, and opinions regarding a given topic. The interviewer, however, must not impose any prior judgements that may hinder either the field of inquiry or the extension of the answers, meaning that interviewees must solely answer on the basis of her/his immediate knowledge and/or opinions (Fontana & Frey, 2000);
- **Hypothesis-directed questions** – Are made to prompt interviewees to make explicit their implicit knowledge, so that researchers evaluate whether or not the theoretical assumptions are valid. This helps to highlight the fragilities of the tool to allow its improvement and finetuning (Flick, 2006);
- **Probing questions** – Are made to push the interviewee to infer and deduct on her/his prior statements along the interview, forcing them to rethink and critically re-examine their presumptions when opposing alternatives are presented (Flick, 2006).

Flick (2006) also argues that, when resorting to interviews as a validation technique, three sequential steps ought to be followed:

- **Record the data** – This can be achieved by either video, audio, or even written records so that the consequent analysis of the interview can be achieved trustworthily and verifiably;
- **Edit the information** – Interviews naturally generate high amounts of data which need to be transformed into valuable knowledge. To accomplish this, the original data needs to be processed by means of, for instance, a full transcription or simply the identification and filtering of the most relevant parts of the interview that fulfil the objectives of the interviewer;
- **Case study analysis** – Case study analysis research methodologies consist in involving empirical research of a specific contemporary phenomenon within its real-life context, making use of more than one source of evidence. Its aim is to capture, in a very detailed and exact way, the situation under study and to allow the linkage between theory and fieldwork information (Saunders, 2009; Flick, 2006). Following the data collection phase, it's time to summarise, categorise, and structure that exact information so as to produce sound and sustained conclusions, meaning a new reality is to be constructed from the generated information (Saunders, 2009).

The next chapter will focus on the materialisation of the aforementioned methodology, serving as a hands-on and practical guide on how to implement Sustainability 4.0, covering its four steps from a user manual standpoint, whereas the sixth chapter will cover the two-stage process of validating Sustainability 4.0.

5. A hands-on guide for the implementation of Sustainability 4.0

This chapter serves as a hands-on and practical guide on how to implement Sustainability 4.0 in an organisation, being, for that reason, the centrepiece of this work. Sections 5.1. to 5.4. cover steps 1 to 4 of the previously presented methodology for the development of a generic version of the tool, respectively.

5.1. Step 1 – System definition

The first step is where the scope of the study is defined. It involves describing the system under analysis. For that, the life cycle of the object under assessment should be depicted to better visualise it. This depiction should be framed taking into consideration Cato's (2009) aforementioned onion-shaped depiction of the three dimensions of sustainability, depicted in figure 3, so as to include and highlight the interactions between them.

For the sake of generalisation, a generic product life cycle, *i.e.*, a life cycle which usually encompasses typical cradle to grave supply chain echelons such as raw material extraction, production, usage, and disposal phases, is used in this work. This is depicted in figure 11. However, when applying Sustainability 4.0 to a real-life context, the end user should design the life cycle that corresponds to the organisation's needs.

To depict the interactions between the three layers, three types of flows were defined:

- **Processual flows** – Flows that represent the moving of materials and/or physical interactions (*e.g.* labour, movements of material and goods throughout the supply chain, *etc.*). These are depicted by a continuous arrow;
- **Monetary flows** – Flows that represent the transfer of monetary quantities. These are depicted by a dashed arrow;
- **Externality flows** – Flows that highlight where externalities, either positive or negative, are generated, *i.e.*, if, when producing or consuming a good, an impact on third parties not directly related to the transaction is created (*e.g.* the extraction of raw material from the surrounding ecosystems is made at the cost of the generation of pollution). These are depicted by thicker dashed and dotted arrows.

The diagram then distinguishes, through four different geometrical shapes, the entities that intervene in the system:

- **Square** – Represents a phase of the life cycle. Should be linked to a physical process/activity;
- **Circle** – Represents an economic intervenient in the process. It can be either a specific department of the organisation or an external entity that has economic influence over the system;
- **Diamond** – Represents the stakeholders;
- **Cross** – Represents the surrounding ecosystems and natural systems, namely air, land, water, and biosphere.

For this diagram, a basic set of stakeholders that can applicable to most cases, was considered. Since stakeholders are either people, groups of people, or organisations, their intrinsic social nature is present by definition. However, some of them play a major role in the economic ecosystem that surrounds the life cycle.

Therefore, stakeholders such as suppliers, competitors, and workers, for instance, are considered borderline intervenient in both the economic and social layers. The only stakeholder that belongs solely in the social layer out of those who were considered, is the local community for not having a strong and direct influence in the economic dimension of the organisation. Additionally, for having identical interests, and influential and decisional power levels, three stakeholders were bundled up together in a single cluster for the sake of simplicity: management and board of directors (BoD), Government and State, and shareholders. It is important to mention that despite also being workers of an organisation, managers and members of the BoD have distinct interests from those of regular workers, hence the segregation of these two actors into two different stakeholder groups.

As it can be observed in the diagram, the generic life cycle of a product is the centrepiece of the diagram, as it is the common denominator between all interactions with the three dimensions of sustainability. The depicted life cycle includes generic supply chain echelons in a cradle to grave perspective. The flows that depict the interactions between the three layers ought to be numerated so that they can be easily identified and described:

- Flows 5, 8, 11, 14, and 19 correspond to the logical downstream movement of material and goods throughout the supply chain;
- Flows 18 and 21 highlight the importance of the customer in the usage and disposal phases, respectively;
- Flow 15 symbolises the monetary transaction associated to the acquisition of the good or service;
- Flow 1 denotes the seizing of raw material from the environment at the cost of generating externalities, depicted in flow 2;
- Flows 3 and 4 represent the monetary transaction and movement of goods associated with the acquisition of raw material from suppliers, respectively;
- Flows 7 and 13 represent the monetary expense generated by logistics activities;
- Flow 22 represents the costs of the reverse logistics processes associated to the disposal phase, if applicable;
- Flow 9 represents the costs associated to the research and development (R&D) activities that have preceded the production phase, if applicable;
- Flow 10 depicts the investment that was made prior to the full operationality of the life cycle;
- Flow 17 represents the costs associated to marketing activities, which are allocated to the usage phase;
- To support the economic activities, there is a bidirectional monetary flow (12) that depicts the investment made by shareholders, governmental entities, and higher ranks of management, if applicable, who decide to invest in exchange of future monetary gains;
- Workers play a central role in the economic activities surrounding the life cycle. They provide labour (16) at the expense of monetary transfers, *i.e.*, wages (20), and creation of externalities (23);
- Local communities that surround the site where the organisation develops its operations are also affected by either negative and positive externalities (*e.g.* effects of pollution and investment in local schools, respectively), which are depicted by flow 24;
- To highlight the impacts the organisation's operations prompt on its competitors, flow 6 was included.

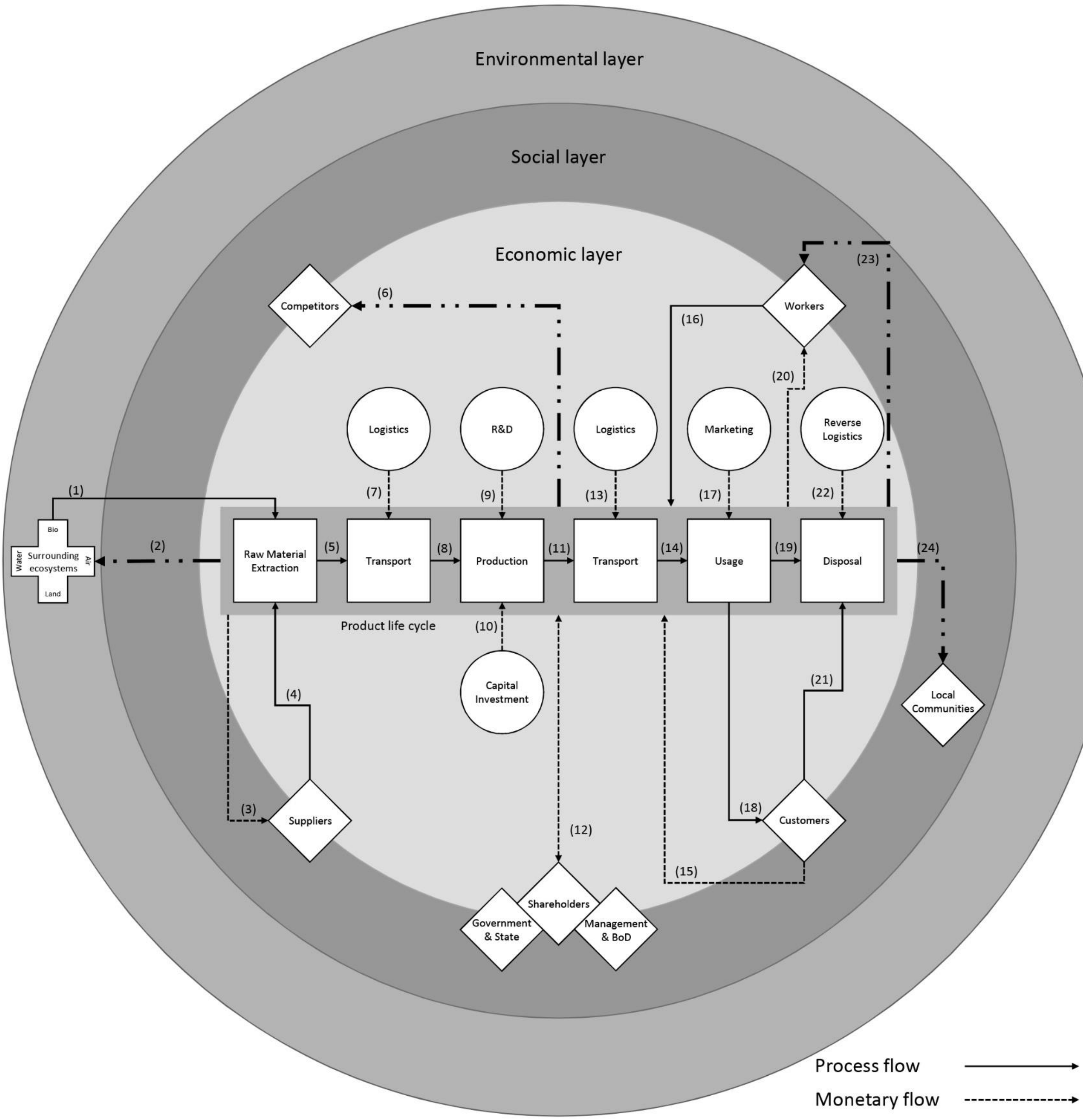

Figure 11 – Depiction of a generic life cycle with its interactions with the three dimensions of sustainability highlighted (source: author based on the works of Cato, 2009)

5.2. Step 2 – Indicator selection

The second step for the development of Sustainability 4.0 is to compile and select the sustainability indicators to be included in the assessment. This step constitutes the centrality of the tool. As mentioned, indicators should be retrieved from the literature and their suitability to assess a subject like the context of smart manufacturing should be, subsequently, evaluated. Any selected indicator must, however, be clearly characterised by means of a clear definition, have its relevance to the analysis stated and sustained, and a mathematical formulation, stating how to perform its computation (Popovic *et al.*, 2017). Additionally, Feng and Joung (2009) state that an indicator, in order to acquire the effective properties of one, must be:

- **Accessible** – Information regarding any indicator can be verified by accessible data;
- **Quantifiable** – Any indicator must be numerically measured, meaning that qualitative indicators are left out;
- **Relevant** – Any indicator must show relevant information about a system, *i.e.*, the object of analysis, meaning that its presence in the assessment is able to be sustained;
- **Reliable** – The information provided by an indicator must be trustworthy and verifiable;
- **Understandable** – The definition of an indicator must be clearly, unequivocally, and easily understandable by all stakeholders.

In this work in particular, since a generic version of the tool is being presented, and as there can be no *one-fits-all* indicator list for all cases, a criteria for the selection of indicators to be analysed needs to be defined. Therefore, the selected indicators are proposed to be categorised into three types:

- **Primary** – Indicators whose presence in the assessment is fundamental. They are the core of the analysis as they look onto the structural and conjunctural changes that are bound to occur with the introduction of industry 4.0 technologies. They should, consequently and as much as possible, be present in the assessment. These indicators should be shrewdly chosen so as to assess any changes in the revenue and cost structure of the organisation, in productivity and quality control metrics, as well as the employee structure, employment conditions, and to the midpoints of a preselected LCIA method, as they are very comprehensive indicators for the environmental dimension. The selection of the aforementioned ReCiPe LCIA method is recommended due to its comprehensiveness (Carvalho *et al*, 2014). In order to integrate LCIA midpoints in the assessment, the organisation must possess the necessary means to obtain it – usually, specialised people and software. If the organisation does not possess such means, indicators suggested by the GRI can be used in substitution, since they take into account, in a more concrete and palpable manner, indicators such as energy consumption or water consumption, *i.e.*, indicators that are directly linked to physical quantities. Lastly, investment analysis indicators should be included in this type of indicators, as the implementation of industry 4.0 technologies requires a great amount of investment;
- **Complementary** – Indicators whose presence in the assessment is considered accessory but would contribute to a more robust and comprehensive study. These indicators are sometimes difficult to

measure (*e.g.* degree of acceptance of an organisation by the local community) but should be present whenever possible. Changes in the socio-demographic characteristics of the organisation's workforce, accessory environmental indicators such as the ones suggested by the GRI and other microeconomic indicators should be understood as complementary indicators;

〉 **Sector-dependant** – The presence or absence of these indicators in the assessment depends on the sector, industry, or market it is being applied to. They are case study dependant as some indicators only make sense in a given context (*e.g.* in a pure service industry, concepts related to raw material extraction may not be applicable and indicators related to animal testing would, for instance, make sense if the assessment was being carried out in a pharmaceutical industry context).

Table 6 summarises the criteria for the categorisation of indicators according to the aforementioned indicator types.

Table 6 – Criteria for the categorisation of indicators to be used in Sustainability 4.0 according to their type (source: author)

Primary	*Used whenever possible*	〉 Those that are essential to a comprehensive and robust assessment of the impacts the introduction of industry 4.0 technologies entails; 〉 Are generally related to the changes bound to occur when making the shift to industry 4.0; 〉 Look for changes in cost structure, productivity, employee structure and benefits, and LCIA midpoints; 〉 Analyse from an investment point of view.
Complementary	*Use if possible*	〉 Those whose presence in the assessment are accessory and, sometimes, difficult to obtain, but complement the analysis in order to sustain it; 〉 Look for microeconomic indicators, socio-demographic characteristics of employees, and accessory environmental indicators such as the ones suggested by the GRI.
Sector-dependant	*Depends on the case study*	〉 Those whose presence in the assessment depend on the type of industry, company, or market it is being used in; 〉 They are case study dependant.

5.3. Step 3 – Framework development

Once the indicators are selected, the end user should decide how the information is going to be presented. A very straightforward way to accomplish it is through the construction of a dashboard. A proposed layout for such a dashboard – one for each of the three dimensions of sustainability –, essentially made up of columns and rows, is presented in figure 12. Each set of columns is described and clarified below.

As mentioned before, the materialisation of this tool can be executed resorting to whichever medium the end user finds most appropriate to work with. For this work in particular, the materialisation of this tool was achieved resorting to MS Excel®. Table 7 depicts a blank MS Excel® spreadsheet on which the basis of the dashboard of Sustainability 4.0 was implemented.

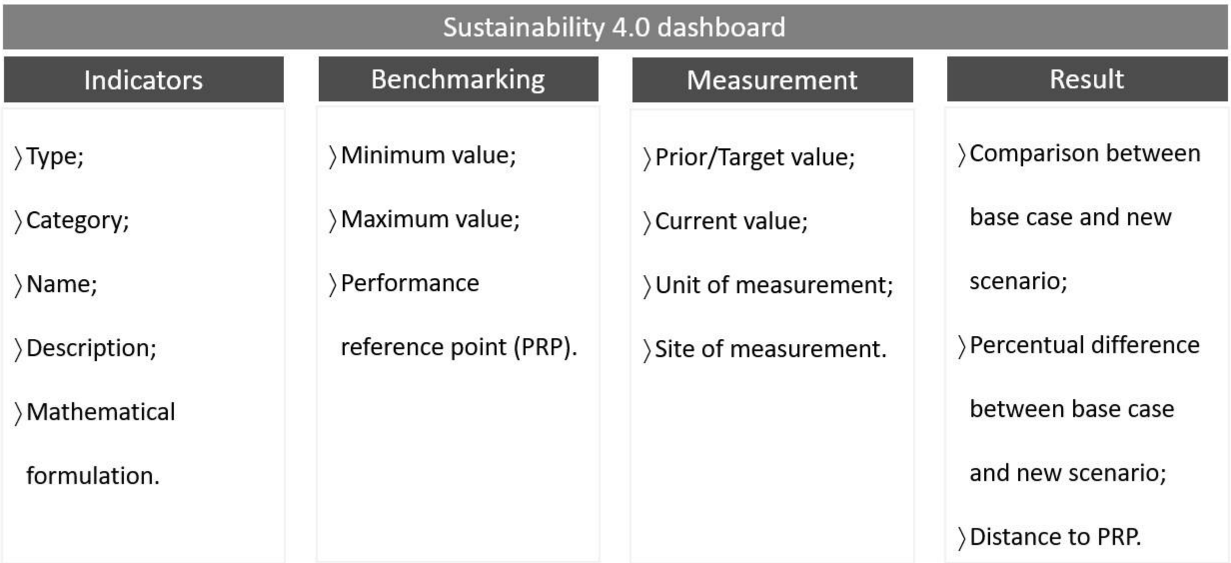

Figure 12 – Generic layout for the dashboard of Sustainability 4.0 (source: author)

Table 7 – Materialisation of the dashboard of Sustainability 4.0: mock-up of a blank MS Excel® spreadsheet depicting the layout (source: author)

Indicators			**Benchmarking**			**Measurement**			**Result**		
Category	Name	Description	Minimum value	Maximum value	PRP	Prior value	Current value	Unit	Improvement /Deterioration?	Difference	Distance to PRP

5.3.1. Indicators

The first set of columns is held in reserve for the indicators segment. Here is where the previously selected indicators are itemised. Each indicator should contain information regarding:

- 〉 Its **type**, *i.e.*, whether it is a primary, complementary, or sector-dependant one, according to the criteria defined and presented in table 6;
- 〉 To which **category** it belongs, *i.e.*, the subject the indicator aims to evaluate (*e.g.* if it is related to productivity issues, if its related to labour practices and decent work, *etc.*);
- 〉 An identifiable **name** – preferably short –, so that it can be univocally recognised;
- 〉 A **description**, so that anyone who uses the tool recognises its relevance, and understands why the indicator is present and what it is measuring;
- 〉 Its **mathematical formulation**, when applicable, by means of an equation, for instance, so that its computation is clear.

For the sake of simplicity and to underwhelm the dashboard, all information, apart from the name, can be remitted to an annex document as long as it can be accessible to the end user.

5.3.2. Benchmarking

The second set of columns is where the basis for comparison is defined. Lower and upper bound values are defined for each indicator, setting a range of values that build the basis for a comparative analysis. These values can be set or obtained through the following means:

- The organisation's own objectives and managerial goals, meaning they are defined internally;
- Existing regulations and legislations (*e.g.* some governmental entities impose restricting values on some pollutants);
- Information available in the literature;
- Data from other organisations whose operations are similar to the ones that are under analysis and are located, preferably, in the same geographic regions (Cadena *et al.*, 2018).

A performance reference point (PRP) can be defined as a way to assess whether or not the current level is in line with this reference value. The *out-of-the-target* indicators, *i.e.*, those who fail to have a lower performance compared to the PRP, are pointed out as the system's hotspots. One way to compute the PRP, according to Cadena *et al.* (2018), is to take the arithmetical average between the lower (minimum) and upper bound (maximum) values. This can be explained and understood as a conversion of the minimum and maximum values to a scale of 0% (worst possible) to 100% (best possible), respectively. The PRP will, therefore, be the figure for which the system obtained a value of 50%.

The PRP is particularly useful to evaluate whether the positive differences that may be identified between prior values and current values, for instance, are in line with what was defined as satisfactory.

5.3.3. Measurement

The third set of columns is where the actual measurement and consequent computation, when applicable, of the numerical values of each of the indicators ought to be displayed. This is, essentially, the cornerstone of Sustainability 4.0, since it is fundamental to understand the effects of the introduction of industry 4.0 technologies. Two measurements are required to make a comprehensive assessment:

- **Prior value** – The numerical value of an indicator in a point of time prior to the introduction of industry 4.0 technologies. It must be present if the tool is to be applied after the implementation of these technologies on the shop floor level, *i.e.*, in a context A situation. The moment in time immediately prior to this implementation is recommended. However, if either the data availability and/or its quality, in any other moment in time before that one, is superior, it should then be considered;
- **Target value** – The numerical value of an indicator whose goal is to attain or surpass it. It must be present if the tool is to be applied during the implementation of these technologies on the shop floor

level, *i.e.*, in a context B situation, as another benchmarking reference to keep track of the success of the implementation. Again, this value can be obtained in the same way as the benchmarking ones;

- **Current value** – The numerical value of the same indicator at the present time. It must be present in either of the tool's applicability contexts.

Additionally, the unit of measurement must be specified, as well as the location, in the life cycle, where the measurement took place. The end user should, for that purpose, resort to the life cycle depiction, namely the names of the entities or the numbered flows, so that the information about the data provenience is clear.

5.3.4. Result

Lastly, the fourth set of columns is a compilation of results stating whether there was an improvement or a deterioration of each indicator, the respective percentual difference between prior and current values (or current and target values), and the difference to the specified PRP, when applicable. Bar charts and/or tornado charts are the recommended graphical mediums to showcase the percentual differences and the absolute values for the indicators, respectively. Cases which either fail to surpass the respective PRP, or in which the percentual difference displays a negative value, meaning deterioration has occurred, are considered a system hotspot.

It is important to note that there is a group of indicators that, despite being a fundamental part of the analysis, ought to be handled in a different way since no comparison between prior and current values is possible. These are the investment analysis indicators, *i.e.*, the aforementioned NPV, ROI, and payback period. Making the shift to industry 4.0 involves a great effort from the investment point of view but that investment is made (or is considered to be made) in a single point of time, making no sense to compare it to any other value. Achieving economic sustainability in such a context naturally implies that investment analysis indicators attain satisfiable levels. However, these can be interpreted without any basis of comparison, meaning its evaluation is made simply by looking at its values. Investment analysis indicators must then be present in this analysis as primary type indicators but should be kept aside from the remaining ones. Moreover, whilst being fundamental to identify the system's hotspots, the definition of improvement and deterioration of an indicator may vary according to the organisation's objectives. Some indicators such as accident frequency, for example, have this task relatively simplified as an increase in the number of accidents is always considered to be a bad thing. However, in some indicators such as percentage of employees who work in a part-time regime, this assessment becomes somewhat subjective. Therefore, the distinction between good and bad should be made by taking into account the scope and the objectives of the assessment, as well as the organisation's strategy.

5.4. Step 4 – Stakeholder engagement plan

The fourth stage of this methodology is the development of an SEP to mitigate (or eliminate, if and whenever possible) the previously identified hotspots. Figure 13 schematises the steps to develop an SEP.

Firstly, the stakeholders of the system under assessment are to be identified. Here, the aforementioned stakeholder identification techniques should be applied, such as Bryson's (2004) Basic Stakeholder Analysis, for instance. Hybrid versions of the many available stakeholder identification methodologies validated by the literature, meaning key elements from several techniques are used simultaneously, are also acceptable, in addition to any other that the end user finds suitable to be employed for as long as a congruent output is obtained.

Figure 13 – Methodology for the definition of the outputting stakeholder engagement plan (based on Cadena et al.*, 2018 and Bal* et al.*, 2013)*

Following the identification of stakeholders, these ought to be classified according to, for instance, their power, interest, and their supportiveness towards change so that the end user can better manage them individually. This can be accomplished using the abovementioned power-interest matrix (Ackermann & Eden, 2011) and the problem-frame matrix (Nutt & Backoff, 1993), for instance. Again, other stakeholder categorisation techniques that the end user may find more suitable to be applied in a given case are also valid as long as a consistent output is obtained.

Then, the requirements of the stakeholders who are associated to a given hotspot ought to be identified and linked to appropriate sustainability targets (Cadena *et al.*, 2018; Bal *et al.,* 2013). For each of the identified hotspots, a stakeholder requirement table ought to be constructed, *i.e.*, there should be as many of these tables as the number of the identified hotspots. The purpose of this table is to list the stakeholder's requirements (*e.g.* increase in wages, environmental and social responsibility, *etc.*), which are then linked to the organisation's own sustainability targets/goals. The stakeholders should be ticked to their respective requirements. Table 8 depicts a clean slate of this table in a generic case where *n* stakeholders were considered to be involved in a given hotspot mitigation/elimination process and a total of *m* requirements were identified.

Table 8 – Proposed layout for the stakeholders' requirements table (based on Cadena et al.*, 2018)*

Stakeholders' Requirements	**Sustainability targets (ST)**	**Stakeholders**			
		Stakeholder 1	Stakeholder 2	**…**	Stakeholder *n*
Requirement 1	ST_1				
Requirement 2	ST_2				
…	**…**				
Requirement *m*	ST_m				

The last step before the definition of the SEP *per se* is to determine any impacts, negative and positive, that will result from the defined actions to mitigate/eliminate the hotspots. For that, an impact table should be constructed – again, one table for each of the identified hotspots. For each of these, a list of the positive and negative impacts that the proposed actions to mitigate/eliminate it will prompt, with regard to a given stakeholder, should be stated. Ideally, an impact-risk score should be assigned to each impact. This can be achieved resorting to the abovementioned risk management methods, namely, the attribution of a score according to the criteria defined and presented in table 2 (which can be inputted between brackets, for instance). Table 9 depicts a mock-up of an impact table considering that *n* stakeholders are associated to a given hotspot.

Table 9 – Proposed layout for the hotspot mitigation impact table (based on Cadena et al.*, 2018)*

	Proposed changes' impacts on stakeholders	
	Positive	**Negative**
Stakeholder 1		
Stakeholder 2		
…		
Stakeholder *n*		

The SEP should, ultimately, establish an involvement strategy for each stakeholder, stating the mechanisms of interaction, *i.e.*, the way the organisation should communicate with each stakeholder during the application process in order to mitigate/eliminate the previously identified system's hotspot, providing, whenever possible, a time schedule for each of them, *i.e.*, to state when the actions present in the SEP should be triggered. All the aforementioned steps allow for the end user of Sustainability 4.0 to acquire much needed knowledge regarding stakeholders, which is crucial when designing an SEP. For instance, the greater the power and interest a given stakeholder has towards the results of the application of Sustainability 4.0, the more intense should the engagement mechanisms be (Cadena *et al.*, 2018). These authors list, as examples of engagement mechanisms, the conduction of interviews and surveys, personal and frequent meetings, group workshops, surveys, and even social media engagement.

In order to visualise what the outputting SEP should look like (and also to help the end user to keep track of its progression), a stakeholder engagement plan table should be constructed. A mock-up of this table is depicted in table 10. Here, for each of the stakeholders that are linked to hotspots (in this case, *n* stakeholders), a list of actions to mitigate/eliminate the hotspots that should be carried out with a given stakeholder are presented, as well as their respective engagement mechanisms. To determine which actions to be carried out, the requirements acknowledged in table 8 should be taken into account, and to decide the most appropriate engagement mechanisms, the results of the stakeholder classification methodologies, namely their power, interest, and supportiveness, should be considered.

Table 10 – Mock-up of the outputting SEP (based on Cadena et al.*, 2018)*

Stakeholders			
Stakeholder 1	Stakeholder 2	**…**	Stakeholder *n*
〉 Action 1.1; 〉 Action 1.2; 〉 **…**	〉 Action 2.1; 〉 Action 2.2; 〉 **…**	**…**	〉 Action *n*.1; 〉 Action *n*.2; 〉 **…**
Engagement mechanism (EM)			
EM_1	EM_2	**…**	EM_n

5.5. Chapter conclusions

This chapter focused on presenting the four steps to implement Sustainability 4.0 from a user manual standpoint, meaning it represents a hands-on guide to its actual application. Sustainability 4.0 allows the identification and characterisation of sustainability hotspots derived from the implementation of industry 4.0 technologies in the shop floor, allowing to set the future course of action for the development of a stakeholder engagement plan to mitigate or eliminate them. The version of Sustainability 4.0 heretofore presented is a generic one as it is meant to be applied in any given case, sector-wise.

The implementation process entails four steps. The first step is where the scope of the study is defined. It involves describing the system under analysis. For that, the life cycle of the object under assessment should be portrayed to better visualise it. This depiction should be built in a way that highlights the interactions of the life cycle with the economic, social, and environmental layers. The second step is to define and select the indicators to be included in the assessment. This step constitutes the centrality of the tool. As mentioned, indicators should be retrieved from the literature and their suitability to assess a subject like the context of smart manufacturing should be, subsequently, evaluated. In order to assist this process, a criteria that assesses the indispensability of each indicator was defined. Then, following the collection and selection of indicators, these ought to be organised so that they can generate valuable inputs to decision-making processes. As such, a layout for a dashboard which captures the information provided by the indicators was proposed. It was built in such a way that allows it to assess the impacts the introduction of industry 4.0 technologies in the shop floor will prompt by comparing prior or target values with the current ones. Indicators that either fail to surpass the predetermined PRP or cases where deterioration has occurred are considered to be a hotspot. The fourth step is, therefore, to develop a stakeholder engagement plan that can mitigate or eliminate those exact hotspots.

In order to validate the scientific legitimacy of this tool, as well as its applicability to a real-life context, a two-stage validation process, involving a focus group and face-to-face in-depth interviews, was conducted. The results are presented in the next chapter.

6. Validating Sustainability 4.0: insights and recommendations

This chapter covers the validation process of Sustainability 4.0. Section 6.1. covers the process of validating a preliminary version of Sustainability 4.0 through a focus group with experts in the field. Section 6.2. covers a further validation stage resorting to in-depth interviews. Section 6.3. outlines this chapter's conclusions

6.1. Preliminary validation via focus group

In this specific case, the usage of a focus group as a technique to validate the heretofore presented methodology for the development of Sustainability 4.0 involved three steps.

The first step was to select the participants of the focus group. The choice fell on three experts in the field, all from the Department of Engineering and Management of the university the author of this work belongs to. To play the role of facilitator, the author of this work was designated.

The second step was to define the way the focus group was going to be carried out so that a productive discussion was generated. Here, the facilitator plays a major role, since it is her/his responsibility to define the topics of the focus group and make sure the discussion is as relevant as possible, guaranteeing that every topic and subject of interest is covered. In this case in particular, the original train of thought that led to development of Sustainability 4.0 was presented. The topics were presented and discussed in the following order:

- Contextualisation of the problem and explanation of the motives that led to the development of Sustainability 4.0 in the first place;
- Presentation of the methodology for the development of Sustainability 4.0;
- Definition of the criteria for the selection of indicators to be present in the dashboard of Sustainability 4.0;
- Suitability of Sustainability 4.0 to assess sustainability issues in a smart manufacturing context.

The third and last step was to collect every piece of feedback from all participants and turn that information into knowledge. As the issues that were brought to the conversation were being discussed, several remarks and improvements, mainly focused on the indicator selection phase, were suggested and later implemented. The version of Sustainability 4.0 heretofore presented is, therefore, a finetuned version of the tool following the validation from the academic point of view through the focus group methodology.

6.2. Further validation via in-depth interviews

Taking into consideration the research question presented in the first chapter, the purpose and objectives for the application of this validation technique presented in chapter 4, and the steps for the implementation of Sustainability 4.0 presented in chapter 5, a semi-structured interview script was elaborated.

Table A1, in the appendixes section of this document, presents the 13 questions that were asked during the course of the interviews. Questions Q1 to Q3 were asked in order to assess the interviewees' perception and presumptions of the way and extent industry 4.0 will impact issues related to sustainability. Questions Q4 and onwards were asked following the presentation and exposition of Sustainability 4.0 to interviewees so that they are aware of the underlying concept and what was about to be discussed. In doing so, interviewees' prior perceptions, presumptions, and knowledge regarding this topic could be assessed upfront and unbiasedly.

The selection of interviewees favoured experts in the field, more specifically, six renowned academics from two European universities, as well as nine individuals whose expertise and knowledge in the topic of industry 4.0 within the Portuguese industrial fabric is widely acknowledged. To guarantee their anonymity, interviewees will henceforth be identified with a letter (**A** if the interviewee is from the academic dimension and **I** if she/he represents an organisation or has a prominent role in an organisation that works closely with industry 4.0 topics) and a number, assigned by scheduling order. For this reason, question Q3 acquires two configurations: the first configuration is asked if the interviewee is someone from the academic dimension and the second is asked if the interviewee is someone from the business dimension. Detailed information about the interviews that were carried out, namely the time and place they occurred, as well as the roles of the interviewees, can be found in table 11.

Table 11 – Detailed information regarding the conducted interviews

Interviewee	Role	Place	Date	Duration
A_1	Associate professor from the Department of Engineering and Management of the university the author of this study belongs to	Interviewee's office	May 6th, 2019 11h00	1h17min
A_2	Auxiliary professor from the Department of Mechanical Engineering of the university the author of this study belongs to and cofounder at a consulting company specialised in lean manufacturing, six sigma, and continuous improvement.	Interviewee's office	May 14th, 2019 09h30	0h52min
A_3	Researcher in the Centre for Industrial Engineering and Management from INESC TEC [a]	Video conference	May 6th, 2019 14h30	0h57min
A_4	Full professor from the Department of Engineering and Management of the university the author of this study belongs to	Interviewee's office	May 9th, 2019 16h30	0h32min
A_5	Scientific assistant at TUD [b] from the Department of Materials Handling and Warehousing	Video conference	May 21st, 2019 10h00	0h42min
A_6	Ph.D. candidate for the Leaders in Technical Industries programme at MIT Portugal	Interviewee's office	May 23rd, 2019 15h00	0h52min
I_1	Project manager at COTEC Portugal [c]	Video conference	May 13th, 2019 14h30	0h47min
I_2	Director at a consulting company aimed at providing business risk and sustainability solutions to organisations	Video conference	May 15th, 2019 09h00	0h59min
I_3	Plant manager at an automobile component manufacturer	Interviewee's office	May 21st, 2019 16h30	0h43min
I_4	Logistics planning manager from the automotive industry	Interviewee's office	May 30th, 2019 15h00	1h10min
I_5	Digital factory manager at an industrial manufacturing systems company	Interviewee's office	June 6th, 2019 10h00	0h36min
I_6	Supply chain flow engineer at a consumer electronics retailer	Video conference	May 22nd, 2019 17h00	0h46min

I_7	Partner at one of the Big Four consulting companies	Interviewee's office	June 3rd, 2019 15h00	0h48min
I_8	Member of the BoD in a Portuguese conglomerate holding company with interests in the cement, pulp and paper, and environmental services sectors	Interviewee's office	May 27th, 2019 15h30	0h43min
I_9	Coordinator of the sustainability department in a Portuguese international property and retail real estate services company	Interviewee's office	May 29th, 2019 14h00	0h48min

[a] INESC TEC – *Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência* (Institute of Systems Engineering, Computation, Technology and Science) was created to act as an interface between the academic world, the world of industry, services, and the public administration in ICT, telecommunications, and electronics;

[b] TUD – *Technische Universität Dortmund* (Technical University of Dortmund) is a university in Dortmund, Germany, with over 35.000 students and over 6.000 staff members, including 300 professors, offering around 80 B.Sc. and M.Sc. degree programs;

[c] COTEC Portugal – *Associação Empresarial para a Inovação* (Business Association for Innovation) is a not-for-profit business association created in April 2003, following an initiative of the President of Portugal. Its mission is to promote the competitiveness of companies established in Portugal through the development and the diffusion of innovation. It is one of the main governmental entities involved in the Portuguese Government's action plan to promote industry 4.0 within the Portuguese industrial fabric.

All interviews were audio-recorded with due authorisation from interviewees. Flick (2006) argues that the naturalness of speech from interviewees is maximised when they are conducted in either their usual workplaces, such as their offices, or their company's facilities. For this reason, it is assumed that, in every interview, interviewees answered to the questions in a natural and genuine manner, meaning there are no significant behavioural differences to be taken into account. The assurance of anonymity also strengthened this feeling of comfort. As a result of the conduction of interviews, a great amount of information was generated. Despite the fact that interviews were audio-recorded, their full transcription is not required since not only is it very time consuming, but also because the true meaning of the message that interviewees are trying to convey may be concealed in a broader sense rather than just its explicit form.

What follows is, precisely, the analysis and processing of the information that was collected during the interviews. For the sake of summarisation, categorisation, and structuring, each of the questions that constituted the interview script, presented in table A1, will be analysed individually, meaning that all the subjects that were brought up to the discussion by all interviewees when a given question was asked are clustered, allowing a better, more fluid, and more perceptible analysis on the obtained feedback. As more interviews were conducted, the interviewees' answers were becoming successively more redundant. As such, whenever this occurred, some accounts were omitted for the sake of summarisation.

Q1 – Do you think that industry 4.0 will allow organisations to achieve better sustainability standards?

The purpose of asking this question is to analyse the degree of awareness interviewees have regarding the concept of industry 4.0, as well as to assess any prior preconceptions and assumptions they have towards the topic of sustainability within smart factories.

Interviewee A_1 began by pointing out that, in the Portuguese industrial fabric, industry 4.0 is still a mirage, in particular for SMEs, due to the high amount of investment that is required in order to implement such technologies in the shop floor as well as the fact that these technologies are still not yet fully commercialised. Another factor that contributes to this hindrance in making this technological shift is that the costs of labour in Portugal are still comparatively low as to other, more industrialised, countries, namely in Europe. For this reason, it still pays off to invest in traditional human resources rather than in automated systems. However, the interviewee highlights that, despite the hindrances, one should not infer that organisations do not what to make this shift. As far as sustainability is concerned, the interviewee points out that industry 4.0 will bring new trade-offs to the decision-making table. The interviewee starts by giving the example that the introduction of these new technologies can be the cause of layoffs due to substitution, but can be, nonetheless, the disrupting factor that leads to better working conditions, namely in the field of ergonomics. The underlying bottom line taken from this interview is that the concepts of sustainability and industry 4.0 are unquestionably complementary, which leads to new decisions having to be made.

Interviewee A_2 also agreed that this technological shift will encourage organisations to become more sustainable and aware of their position in terms of sustainability practices and results. This interviewee points out the greater availability of information, as well as its trustworthiness, as the enablers of this increase in sustainability standards. This is because one of the main reasons why organisations disregard sustainability. It is related to the high amount of data and information that is usually scattered throughout several departments or entities. This leads to a state of obliviousness by managers who, even if they are aware of the importance of sustainability, are unable to keep track of their current position, let alone trace a sound strategy to enhance sustainability standards within the shop floor. Industry 4.0 technologies, namely their real time measurement capabilities and interconnectivity, may contribute to the centralisation of this information, providing decision-makers with substantial information on which to sustain their future actions.

Interviewee A_3 goes in the same direction as what has been discussed so far, affirming this technological shift will definitely contribute to make more sustainable decisions and design greener processes in the future. The interviewee's background in the field of civil engineering allowed to get a different perspective of how industry 4.0 can be implemented in the construction sector, proving it is truly transversal to several areas of engineering and business sectors.

Interviewee A_4 was also peremptory in affirming that the introduction of these technologies throughout the industrial fabrics will undoubtedly contribute to boost sustainability standards within organisations. However, this will only be true if this technological shift is made while having this goal in mind, meaning organisations should take into account the impacts it will prompt upfront.

Interviewee A_5 also answered affirmatively and mentioned the example of IoT as the main enabler to optimise production and logistics systems, which, due to the CPS, become interconnected and self-aware of what is happening, allowing, for instance, for greater energy consumption and resource utilisation efficiency.

Interviewee A_6 argues that, despite recognising that the introduction of industry 4.0 technologies will improve the efficiency of the operations, overall, the expected increase of the productive capacity that goes together with this fact will, eventually, be the cause for a worsening of environmental sustainability standards.

The bottom line is that industry 4.0 has the potential to make organisations more sustainable but this will ultimately depend on how organisations choose to implement it.

Interviewee I_1 answered affirmatively and mentioned several examples to sustain this opinion. The interviewee mentioned the concepts of energy management, meaning that the CPS and smart factories will, inherently, hold the capability of managing their energy consumption in real time, allowing for a more efficient use; and resource management, in which the inputs of a process will be optimised continuously and in real time, allowing for a reduction of waste. An expected disruption in areas such as quality control and logistics was also mentioned. The impacts of industry 4.0 are transversal to the value chain and, as such, many other impacts in terms of sustainability will certainly arise.

Interviewee I_2 believes industry 4.0 will provide organisations the ability to optimise resource consumption and mitigate some of its previous impacts. Overall, this will inherently contribute to making organisations more sustainable.

Interviewee I_3 argues that industry 4.0 will, above all, make information regarding operations much more visible and accessible. Given this, whether industry 4.0 itself will improve the sustainability standards of an organisation will ultimately depend on the way businesses decide to use this information. The fact that the organisation possesses more information regarding its processes alone does not guarantee that it will be used – in fact, it will only generate more chaos. It is the subsequent filtering, processing, and analysis of this data that will be the key to generate powerful information and knowledge that could, eventually, be used in order to make more sustainable decisions. This falls in the fields of data science and data mining.

Interviewee I_4 started by mentioning that the improvements in the environmental dimension will be particularly notorious. When referring to the economic dimension, it was mentioned that in the organisation the interviewee belongs to, investments are only made if they are intended to bring cost reductions, as they are very cost orientated. Regarding the social dimension, it was agreed that this is the most complex dimension when making decisions, but it was stated that the fear of suppression of jobs is an inherent characteristic to all industrial revolutions and that the loss of some jobs in the present will guarantee the long term survival and competitiveness of the organisation so that it can hire even more qualified people in the future.

Interviewee I_5 states that "it is obvious that it will". Resource optimisation will enable organisations to save on some superfluous costs, to become more transparent, and to harmonise processes throughout the value chain, allowing for some time savings.

Interviewee I_6 also states that this will only be true if organisations take advantage of the potential industry 4.0 technologies have in order to accomplish it. In particular, any improvement in the social dimension will depend, ultimately, in the way society as a whole will face this revolution, meaning it is not entirely up to organisations to guarantee this.

Interviewee I_7 also agrees with the question because "everything that is related to industry 4.0 is bound to potentiate efficiency". The premise of having the same outputs with fewer inputs that is characteristic of industry 4.0 is, *per se*, sufficient motive for organisations to become more sustainable. Additionally, some of the technologies that are perceived to be part of the fourth industrial revolution are, by design, greener and eco-friendly, which is another argument to support the answer. It was also mentioned that this shift will democratise the access to the labour market, specifically in the qualified labour sector, due to the decentralisation of production systems.

Interviewee I_8 answered affirmatively and peremptorily that, by definition, industry 4.0 is bound to help to make organisations more sustainable.

Interviewee I_9 also answered affirmatively and mentioned the fact that industry 4.0 builds the basis of circular economies, which, by definition, are bound to make organisations more sustainable.

Table 12 summarises the inferred awareness of interviewees regarding the topic of sustainability within smart factories. Overall, interviewees' believe industry 4.0 will be a positive game changer when it comes to sustainability issues.

Table 12 – Interviewees' inferred awareness of the topic of sustainability within smart factories (source: author according to the interviewees' feedback)

	A_1	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**	**I_1**	**I_2**	**I_3**	**I_4**	**I_5**	**I_6**	**I_7**	**I_8**	**I_9**
Very positive outlook		X	X		X		X				X		X		
Mildly positive outlook	X							X		X		X		X	X
Neutral outlook				X					X						
Mildly negative outlook						X									
Very negative outlook															

Q2 – Which dimension of sustainability (economic, social, or environmental) will be most affected, either positive or negatively, from the implementation of these technologies?

Interviewee A_1 states that, considering the supply chain as a whole, the environmental dimension of sustainability is the one that will, most likely, be the least affected with the introduction of industry 4.0 technologies since this technological shift focuses on operations and the shop floor rather than logistics, so there won't be any disruptive changes in that field that result in an improvement in environmental terms. Additionally, the economic dimension was pointed out as the most likely to be affected due to the perspectives of gains in productivity, efficiency, and effectiveness. Nonetheless, the impacts in the social dimension were also mentioned, namely the expected improvement of work conditions and the possibility of layoffs due to employees being replaced with machines.

Interviewee A_2, on the other hand, was quick to appoint the social dimension as the one that will be most impacted and in a positive manner. Despite recognising that there will be, undoubtedly, unskilled fringes of the workforce at risk of having their jobs supressed, this is something that can had occurred in all of the previous industrial revolutions and that the bottom line is that the quality of work and the work conditions have always suffered a tremendous improvement. The interviewee also mentioned the expected gains in productivity as predictable impacts on the economic dimension. Regarding the environmental dimension, the efficiency in resource utilisation due the vertical and horizontal integrations, which are two of the premises of industry 4.0, were pointed out. Nonetheless, the interviewee stated that this analysis can't be done with precision because industry 4.0 has not yet, to the eyes of the interviewee, been effectively implemented and that, unlike all previous revolutions, the awareness and knowledge about this particular revolution has been generated prior to the occurrence of the revolution itself, which can be an advantage to decision-makers.

Interviewee A_3 listed the expected improvements in terms of productivity and quality as the impacts in the economic dimension, the reduction of the communication gap between organisations and customers as the most important impact in the social dimension, and the efficiency in resource utilisation as the main impact in the environmental dimension of sustainability.

Interviewee A_4 mentioned that the economic dimension will be the one that will, undoubtedly, be the most impacted in a positive manner. The social dimension was also mentioned as one of the most impacted. However, whether these impacts are positive or not will depend, once again, on how that technological shift is made, *i.e.*, if the impacts that it prompts are taken into account. The positive impacts that will arise in the environmental dimension were also slightly covered.

Interviewee A_5 was quick to mention the environmental dimension as the most impacted because society, and in particular young adults, are become more aware of the obligation organisations ought to have towards this dimension and, since industry 4.0 will allow to make sustainability more visible due to the possibility of real time data collection, this should motivate companies to become more transparent with regard to the environmental impact of their operations. This, in its turn, is strongly linked to the social dimension since the expected improvement of environmental sustainability standards will, consequently, improve some in the social dimension.

Interviewee A_6 argues that the positive impacts in the economic dimension are the most visible sides of industry 4.0. The improvement of working conditions were also pointed out as a huge positive impact in the social dimension, despite recognising that there are also some negative impacts. As to the environmental dimension, it will depend on the managers' mentality.

Interviewee I_1 acknowledged the importance of the social dimension when making the shift, especially with the expected improvement of the work conditions and the need to train employees. However, the economic dimension was referred as the main driver for the implementation of these technologies in the first place and the one whose positive impacts are more easily identifiable, namely the optimisation of resources and energy, and the creation of a new, more direct and instantaneous, communication channel between the organisation and its customers. The environmental dimension was also mentioned as one that will suffer positive changes.

Interviewee I_2 argues that all dimensions will be equally impacted, but, due to the interviewee's background in environmental engineering, the emphasis was put on the environmental dimension. However, the social and the economic dimensions were also mentioned as areas that will suffer disruption.

Interviewee I_3 defends that all apparent environmental concerns are made for marketing reasons and that there isn't a real concern for this dimension. The only dimension that businesses really care about is the economic one and, until economic sustainability is secured, there will not be any form of consideration for the others.

Interviewee I_5 quickly pointed out the economic dimension as the most impacted in a positive way mainly due to expected increases in productivity, efficiency, and effectiveness, as well as the ability to become much more flexible. In the social dimension, it was mentioned the likely upskilling of the workforce rather than the fearmongering of job suppression as the most prominent impact. Despite recognising that the suppression of jobs will be a reality, the interviewee argues that the increase of the level of qualification of the workforce is far more beneficial. As to what the environmental dimension is concerned, the interviewee recognised the role of societal pressure in putting this dimension in a more central position of decision-making processes.

Interviewee I_7 was also quick to point out the economic dimension as the most positively impacted, having stated, as arguments, the relatively small investments required to implement industry 4.0 technologies in the shop floor – since it is implementable in the current manufacturing systems –, as well as the growth of services related to the industry (*e.g.* AI, data analytics, IoT, *etc.*). In the environmental dimension, the expected intensification of the energy usage and the possibility of energy optimisation provided by the CPS were mentioned as impacts. As to what the social dimension is concerned, the interviewee reiterated the democratisation of the labour market and the decentralisation of the industrial fabrics, meaning they no longer have the need to be concentrated within the same geographical region.

Interviewee I_8 argues that all three dimensions will be impacted in an equal way, since "no organisation perdures in time if sustainability, in each of the three dimensions, is attained". A good financial performance is needed, good social relations need to be maintained with stakeholders, and compliance with environmental standards needs to be attained.

Interviewee I_9 stated, very peremptorily, that the environmental dimension is the one that will be most impacted in a positive manner, whilst the social dimension will endure mostly negative impacts. The economic dimension will also be positively impacted, though in a smaller degree. The perceived expected suppression of jobs and/or the consequent upskilling played a major role in this answer.

Table 13 aims to summarise the interviewees' inferred perception with regard to the most and least impacted dimensions of sustainability with the introduction of industry 4.0 technologies. Overall, interviewees' believe the environmental dimension will be the least impacted whereas the economic and social dimensions are typically pointed out as the most affected.

Table 13 – Interviewees' inferred perception on the different impact extension in each of the three dimensions of sustainability (source: author according to the interviewees' feedback)

	A_1	A_2	A_3	A_4	A_5	A_6	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9
Most affected dimension	Economic	Social	Social	Economic	Environmental	Economic	Social	Environmental	Economic	Social	Economic	Social	Economic	/	Social
Least affected dimension	Environmental	Environmental	Economic	Environmental	Economic	Environmental	Environmental	Economic	Environmental	Economic	Environmental	Environmental	Environmental	/	Economic

Economic dimension | Environmental dimension | Social dimension

Q3 – Do organisations, when implementing such technologies, take into account the possible impacts that may arise in terms of sustainability? / Did your company, when implementing such technologies, take into account the possible impacts that may have arisen in terms of sustainability?

Interviewee A_1 considers that organisations effectively do take into account sustainability factors when making these decisions. However, since most companies the interviewee maintains contact with do not have these technologies fully implemented, it's hard to assess if this is a real concern for them.

Interviewee A_2 goes in the opposite direction, affirming, very pressingly, that organisations only look into the economic dimension of sustainability when making the shift.

Interviewee A_3, in its turn, agrees with interviewee A_2, stating that the organisation only looks onto the economic dimension of sustainability and that the remaining two continue on being disregarded.

Interviewee A_4 agrees with interviewees A_2 and A_3, referring, yet again, that organisations only consider the economic dimension. Despite recognising that the interviewee's opinion can change, it was mentioned that, as of the moment the interview was conducted, only the organisations that had attained a sufficient level of technological maturity had been able to make the shift to industry 4.0 and that these were, expectedly, well aware of the impacts it would prompt in all of the three dimensions of sustainability. However, and in any case, until economic sustainability is achieved, the other two dimensions will continue to be disregarded.

Interviewee A_5 argues that this is something that is concerned directly with the way top management looks at this issue and that no generic judgments can be inferred. However, it was mentioned, yet again, that the economic dimension is the one that organisations tend to prioritise.

Interviewee A_6 argues that the topic of sustainability is not used as an input to the decision-making process but as more of an opportunity for the organisation to market themselves as sustainable and transparent.

Interviewee I_1 believes sustainability is, in fact, taken into account when making the shift. However, the economic dimension is the one that takes the top priority as it is the trigger for the decision of implementing these technologies. From the hands-on contact the interviewee has with enterprises who wish to make the shift, they manifest concern with the impacts it will prompt in the social dimension, namely the opportunity to upskill the workforce in order to free them from repetitive, monotonous, and with little added value jobs. The environmental dimension is also a concern, but it tends to be put aside and considered as something "extra".

Interviewee I_2 argues that organisations that decide to make the shift have a direct concern regarding the economic dimension of sustainability but tend to keep, yet in an indirect manner, a concern regarding the other two dimensions because these topics are, in a practical sense, indissociable.

Interviewee I_3 states that, as a plant manager and one of the main decision-makers in that organisation, sustainability, in all of its three dimensions, is, in fact, taken into account. "Nothing is done or implemented just because it is simply in vogue".

Interviewee I_4 stated that "the main driver is purely economic, the secondary driver is the environment, and the social dimensions tends to be put aside". This means the economic dimension is the one that, inherently, organisations tend to focus on. However, and mainly due to societal and sometimes governmental pressures, the environmental dimension is increasingly taking a more prominent place in decision-making processes. The social dimension is the one that, to the eyes of the interviewee, remains as the most disregarded one.

Interviewee I_5 argues that this is something that depends on the organisation itself. Large organisations are more predisposed to look onto these matters in comparison to SMEs, for instance, since they hold far more resources in order to be more transparent and sustainable.

Interviewee I_6 argues that the economic dimension is inherently considered and that any concern with the environmental dimension is merely due to regulatory pressures. As to the social dimension, since there this is a field where legislation is more relaxed, it ends up being the most disregarded dimension.

Interviewee I_7 argues the economic dimension is always taken into account but that the environmental dimension is successively gaining importance mainly due to societal pressures. As to what the social dimension is concerned, it was agreed that this is the most disregarded dimension.

Interviewee I_8 stated, very poignantly, that "organisations must have a consideration for sustainability", since they face serious risks when not doing it. Due to the interviewee's background as member of the BoD of several organisations whose operations where inherently pollutant (cement and pulp & paper sectors), the interviewee argues that, in these cases, sustainability already takes a prominent place in decision-making processes and that metrics for the assessment of sustainability are tracked frequently.

Table 14 aims to summarise interviewees' inferred perception on whether or not organisations do take into account the topic of sustainability in their decisions. Interviewees from the academic dimension tend to be more sceptical towards this fact than the ones from the business dimension. However, perception tends to be either neutral or positive rather that negative.

Table 14 – Interviewees' inferred perception of how organisations consider the topic of sustainability, in its three dimensions, in their decisions (source: author according to the interviewees' feedback)

	A_1	A_2	A_3	A_4	A_5	A_6	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9
Positive outlook	X						X		X				X	X	X
Neutral outlook				X	X	X		X		X	X				
Negative outlook		X	X									X			

Q4 – Do you think that Sustainability 4.0 will be useful to assess whether the implementation of industry 4.0 related technologies within organisations was done/is being done in a sustainable way?

Interviewee A_1 considers Sustainability 4.0, as it was presented, will, effectively, deliver on its purpose in a very straightforward way. The fact that the tool segments the analysis into the three dimensions of sustainability will help end users to understand which dimension is being most affected so that proper actions can be taken more effectively. One thing that was also brought up by the interviewee is that the lack of knowledge and/or awareness towards the concepts of social sustainability and LCA may hinder the analysis, hampering its potential. The exact opposite occurs with the economic dimension since the majority of the data that is required for the application of Sustainability 4.0 to the economic dimension is always available due to the fact that it is required by law. However, the full potential of the tool can only be unravelled if a previous customisation stage is performed.

Interviewee A_2 believes that the scope of the tool itself is much wider than just to assist decision-making processes in the context of industry 4.0. It is also suitable to assess sustainability in any given context in which there has been a change, disruptive or not, from any point A to any point B in time. In this sense, the interviewee considers that organisations will not use this tool specifically to assess sustainability in making the shift to industry 4.0 but are likely to use it in other contexts. This interviewee therefore looks at this tool more as a sustainability tracker rather than just a tool to assess sustainability in the context of industry 4.0. In this logic, the context of its usability only defines the indicator list to be present in such an analysis. As a suggestion, the interviewee stated that, in case a target value is defined, the use of Hoshin Kanri and Balance Scorecard frameworks can be used. An Hoshin Kanri framework is usually employed in the fields of quality management and lean manufacturing. It aims to segment strategic long-term goals into short and easily achievable milestones, simplifying the process of attaining those long-term objectives. This also contributes to motivate stakeholders who intervein in the process of goal-realisation (Hutchins, 2016). The Balance Scorecard framework, in its turn, is also used to implement and manage the process of attaining strategic goals. It connects a vision to a strategic goal, KPIs, targets, and initiatives, whilst balancing performance measures, financial resources, and objectives related to other parts of the organisation. It is, therefore, mostly a business performance management tool (Kaplan & Norton, 1992).

Interviewee A_3 also agrees that the tool is very useful to address the question of sustainability in the context of industry 4.0 and that its biggest contribution is the fact that it provides a framework on which to centralise data that is usually scattered throughout several departments.

Interviewee A_4 agrees that, due to its framework, Sustainability 4.0 will be appropriate to deliver on what it proposes, *i.e.*, help decision-makers to make more sustainable decisions. The key for the success of Sustainability 4.0 is the adequation of the indicators to be present in the assessment to the needs of the organisation in which it is being applied to.

Interviewee A_5 brought up an interesting question: if this tool is meant to assess sustainability in the context of making the shift to industry 4.0, what would the definition of introducing industry 4.0 technologies in the shop floor be? This falls in a similar concept brought up by interviewee A_1 when mentioning that there should be a digitalisation index associated to the application of this tool. This interviewee also agreed with interviewee A_2 when mentioning that this tool could be used to assess sustainability in the context of any form of organisational change, regardless if that change corresponds to the shift to industry 4.0 or not.

Interviewee A_6 states that the methodology for the development of Sustainability 4.0 itself is very well designed to tackle this problem. However, the indicator selection step is the biggest obstacle for its application because, not only it is the centrepiece of the tool, it is the most time-consuming step. Unless organisations acknowledge the value of the tool, they will tend not to commit on implementing such time-consuming processes. The concept of an indicator catalogue was, once again, mentioned as something that would be beneficial. In fact, this was materialised in the possibility of developing a comprehensive and collaborative database of indicators and a subsequent software version of Sustainability 4.0.

Interviewee I_1 believes this tool can add value to the operations of the organisation. One thing that was mentioned was the adequation of the terms employed in the tool and its presentation to the ones that the organisation in which it is being applied to so that everyone speaks the same language. The key to a make Sustainability 4.0 a suitable tool to address the issue of sustainability in an industry 4.0 context is to make it saleable as such, highlighting the benefits it brings to the organisation as a whole.

Interviewee I_2 argues that organisations are overloaded with work and that, despite recognising the potential of the tool in order to accomplish it, they will not, by their own means, apply it, and that the only way this could be implemented is through external consultancy services. It's not an issue of organisations not acknowledging the value the implementation of Sustainability 4.0 may bring, but more of an issue of organisations not possessing the resources required to do it, especially for such a time-consuming process like this one. This interviewee mentioned the same issue that was brought up by interviewee I_1 when saying the tool needs to be “translated into the language that is spoken by the organisation”, meaning the tool should be adapted to the organisation’s own standard procedures and employed nomenclature, leveraging and streamlining the process of its application. It was also mentioned that the presence of a set of columns that allow the benchmarking of the indicators is something that adds great value to the tool. When asked to comment past replies that mentioned the application of Sustainability 4.0 as part of a package of consulting services, the interviewee agreed, affirming the next logical step would be a possible commercialisation of the tool.

Interviewee I_3 would need to see the tool being implemented in a real-life context in order to be able to confidently answer to this question. However, it was mentioned that the general framework of Sustainability 4.0 is likely to deliver on what it promises to do in a very intuitive manner.

Interviewee I_5 states that, from what was presented, the tool has all it takes to, “in a technical and scientific way”, deliver on what it promises to accomplish.

Interviewee I_6 agrees with the question but argues that it would be much more useful in early stages of the decision to implement industry 4.0 rather than during that implementation or even after that implementation is considered to be complete.

Interviewee I_7 also agrees with the question. However, the interview pointed out that the differences that may be identified between the prior and current values, for instance, may not be fully attributable to the implementation of industry 4.0 technologies in the shop floor *per se*, *i.e.*, the tool may not capture the isolated effects of this technological shift.

Interviewee I_8 states that, in order to be able to answer to this question, the interviewee would need to see the tool being tested in a real-life context, namely, to be put through a trial and error process.

Overall, interviewees’ receptivity to the tool was very positive, claiming that, as it was presented, it has all it takes to assess sustainability issues in an industry 4.0 context. However, most of the interviewees stated they would need to see it applied to a real-life situation in order to correctly answer to this question. It was also mentioned that Sustainability 4.0 has the ability to track changes in sustainability standards in the context of any organisational change, from any point A to any point B in time.

Q5 – Do you believe that organisations are willing to use this tool to assess whether this technological shift was made/is being made in a sustainable manner?

Interviewee A_1 believes this is a way for companies to market themselves as greener and more sustainable, which is something that an increasing share of customers are starting to demand. This approach to sustainable smart factories also allows organisations to adopt transparent communication strategies with their customers by applying a standardised method that assesses sustainability practices in their operations. For these reasons, this interviewee is optimist about the application of this tool in a real-life context.

Again, interviewee A_2 believes organisations are, in fact, willing to use this tool but to assess any organisational changes rather than to address the issue of industry 4.0 *per se*. The interviewee also recognises that some organisations already have similar tools but with a very reduced number of indicators – “around 5 to 10” – but whose analysis has a very narrow scope, meaning it is meant and purposefully designed to assess very specific and somewhat technical aspects rather than a broader issue. Additionally, one question that was raised is that the application of Sustainability 4.0 in a given organisation – and, in particular, SMEs – should initially be performed by external and specialised personnel, meaning it should be included in a package of consultancy services since the organisation itself is likely to be mostly unaware of the concepts that surround it and are the basis of the tool.

Interviewee A_3 agrees with interviewee A_1, mentioning that the ongoing trend is an increasing awareness and responsiveness of organisations towards the topic of sustainability, in all of its three dimensions.

Interviewee A_4 also agrees that organisations would use this tool in a real-life scenario.

Interviewee A_5 states that organisations will only use the tool if they understand its potential and know how it can be used in a practical sense.

Interviewee A_6 argues, yet again, that the application of this tool is dependent on the use of assistance, namely by external consultancy services, because, even if the tool is correctly implemented, this would guarantee that the potential of the collected information is, effectively, maximised.

Interviewee I_1 believes it could be used by organisations and goes in the same direction as interviewees A_1 and A_3 by saying that this tool could only be implemented when supported by some kind of external consultancy service and that the issue of commercialisation and making the tool saleable would be of great importance. Another feasible option was the creation of an internal team dedicated to employing such a tool, but this would require the organisation to recognise and acknowledge the benefits of its application.

Interviewee I_3 exhibited some scepticism regarding this question and stated that, when the plant the interviewee manages decided to make the shift, the implementation was made and, only in the end of the process, were the impacts mitigated, meaning the complete opposite of what this tool intends to accomplish. It was brought up the question that, during this implementation, some people had to be laid off. The interviewee's stand on this question is that, despite the laying off process, the shift allowed the organisation to become more competitive and, therefore, more economically sustainable in the long-term, ensuring its survivability. This would secure the remaining workers and allow for the organisation to hire more people (if not the same) in the future.

Interviewee I_4 could not answer to the question in detail nor in a sound way because a real-life implementation of the tool would need to be made. However, the interviewee's feeling is that the presented methodology has all it takes in order to deliver on what it promises to accomplish.

Interviewee I_5 reiterated that only large organisations would be willing to use this tool since they hold much more resources in comparison to SMEs that would be less enthusiastic in employing it.

Interviewee I_7 tends to agree with the question. However, this would depend if the selected indicators were able to isolate the effects of the introduction of industry 4.0. Additionally, the interviewee went in the same direction as interviewee I_2 when stating a GRI-only version of the tool would be ideal since organisations are already aware of these standards, which would streamline the process of application.

When asked if, resorting to the expertise of interviewee I_8 in managing an organisation that operates in a polluting industry (cement industry), the interviewee's organisation would use this tool, the answer was that the company already has their own tools and methodologies to assess their performance in terms of sustainability, mainly due to the regulatory pressures the organisation must comply with. However, and to answer to the question that was asked, the interviewee reiterated that a real-life context application of the tool would need to be made to allow for that question to be trustworthily answered.

Overall, interviewees consider, almost unanimously, that the application of this tool in an organisation is dependant of the use of external consultancy services so that the full potential of the tool can be unravelled. It was also stated that large organisations tend to be more receptive to these kinds of tools, as they possess far more resources that SMEs, for instance.

Q6 – Do you think the application of this tool to a real-life context is feasible?

Interviewee A_1 believes the high amount of data, namely the extensive list of indicators that is necessary for a comprehensive assessment of sustainability, as well as some degree of subjectivity associated with the definitions of "prior value" and "current value", may hinder the full potential of the tool. The interviewee pointed out the following facts to justify that a correct application of Sustainability 4.0 can be very time consuming may even be limited: "if investments [which here can be interpreted as steps for the implementation of industry 4.0 technologies in the shop floor] are spaced out in time rather than made in a single point in time, how can the tool be applied in such a scenario so as to guarantee the isolation of impacts?". A suggestion of resolution for this problem is that, until the shift to industry 4.0 is considered to be complete and fully operational, the end user is in a context B situation – taking into account the two possible contexts of application defined in the fourth chapter – and the investment is considered to be made in a single point in time for the purpose of the application of the investment analysis indicators. However, this raises the question of how can the end user of Sustainability 4.0 define whether the shift to industry 4.0 is complete, *i.e.*, how can the degree of digitalisation of an organisation be measured in a similar way as to the aforementioned DESI index (EU, 2018)? One other important topic that was also brought up to the discussion is that the current value of any indicator, in the case where this measurement is not being performed in real time, must have a well-defined and predefined measuring periodicity that should, ideally, be the same for all indicators so as to guarantee an unbiased assessment.

Interviewee A_2 found it difficult, yet again, to answer this question due to the fact that it has never been, effectively, implemented. However, the interviewee mentioned that the correct implementation and application of this tool would take its time and should not be rushed. Additionally, the decision of implementing Sustainability 4.0 in an organisation belongs to the strategic planning tier, meaning it is a decision that is usually made by higher degrees of management and that should involve all departments. It was also mentioned that the feasibility of the application of this tool would depend on the resource availability in order to accomplish it, meaning that, for instance, if an organisation does not possess the means to conduct an LCA and the tool is dependent on such, the organisation would not use it. This is where the environmental indicators provided by the GRI play a big role, as they usually look onto physical quantities and other easily and directly measurable data, encouraging organisations to resort to these indicators.

Interviewee A_3 also struggled to answer to this question in a direct way for the same reasons as of interviewee A_2. However, the interviewee tends to agree with the question because the interviewee has not seen "anything better so far". Additionally, it was also mentioned that one aspect that can hinder the application is the partial subjectivity that is attached to the selection of indicators, namely their distinction and categorisation according to its type (primary, complementary, and sector-dependent).

Interviewee A_4 believes that the tool is actually quite simple to use. The fact that the tool is, in this case, implemented in an MS Excel® spreadsheet, which is a tool any organisation has available, is also a plus. The only question that may hinder the application of Sustainability 4.0 is the selection of indicators. Organisations – and in particular SMEs – may not be aware of the kind of indicators that should be present in the assessment. This fact alone may be presented as a reason for not implementing Sustainability 4.0 since they are unaware and unconscious of its benefits.

Interviewee A_5 also mentioned that the application of Sustainability 4.0 to a real-life context would only be feasible if it were to be either presented and explained to the organisations or through the use of external consultancy services. Additionally, to create a more interactive version of the tool, meaning the tool would be adapted to become a step-by-step guide for its application, and would streamline this process.

Interviewee I_1 mentioned that the feasibility of the application of this tool to a real-life context is directly correlated, not only with the effort required to conduct a comprehensive indicator collection process, but to the complexity involved in collecting the necessary data in order to obtain or compute the indicators themselves.

Interviewee I_9 referred that, in some indicators, the changes from the prior to the current value may not be explained by the introduction of industry 4.0 technologies *per se*. The interviewer mentioned a practical example to better clarify this topic. The literature recognises an indicator that assesses the percentage of women in management positions (Popovic *et al.*, 2018). If there happens to be a change in this indicator, it may be unlikely that this can be solely explained by the fact that industry 4.0 had been introduced. The interviewee agreed. Therefore, there should, naturally, always be a critical analysis subjacent to the indicator choice.

Overall, interviewees believe that the application of this tool to a real-life context is feasible. However, most of them were keen on pointing out that the step where the indicators are selected is the most complex and time-consuming, representing the tool's Achilles' heel.

Q7 – Do you think that the large amount of data that is necessary for a comprehensive analysis may hinder its application?

Interviewee A_1 states that all assessments involving the usage of indicators are typically very time-consuming. The complexity of the analysis will, naturally, increase with the number of indicators that constitute the dashboard and with the complexity involved in their measurement (*e.g.* to measure the degree of acceptance of the organisation by the local community is considerably harder than to measure cycle times, for instance). The fact that the end user is required to perform a literature review in order to obtain an indicator list to be a part of the dashboard is, itself, a very time-consuming task, let alone all the other steps. A trade-off between the comprehensiveness of the analysis and the time available for its application therefore arises. The designation of an "indicator-owner", *i.e.*, someone who is designated to be kept responsible for the recurrent measurement of a given indicator, was suggested by the interviewee as one way to overcome the dispersion of sources of data that would naturally occur in such an assessment.

Interviewee A_2 considers that this is mostly a problem of SMEs, as most large organisations usually keep track of every detail of their operations. What frequently happens, nonetheless, is that large organisations, despite having all the means to track what is happening in the operations, neither analyse nor use that data to sustain their decision-making processes. This is, again, one of the reasons why this interviewee mentioned that the application of Sustainability 4.0 in the shop floor is pendent on the use of external consultancy services that can assist the organisation with this task and to unravel the full potential of the tool. The key to guarantee that the tool will effectively be used by the organisation is to show them that this can be the way for the attainment of previously set strategic managerial goals that are related to the topic of sustainability.

Interviewee A_3 was peremptory in affirming this is, precisely, the biggest disadvantage of Sustainability 4.0. However, it was suggested that the implementation of this tool was assigned to a sustainability department that, if inexistent, should be created.

Interviewee A_4 agrees with the question while stating, nonetheless, that this is not a critical aspect. The interviewee reiterated that the choice and adequation of indicators to be present in the assessment is the most critical aspect.

Interviewee A_6 also agrees that, as long as organisations are fully aware of the beneficial outputs of the tool and its value, time is not a critical issue. It will always be a trade-off between time, resources, and benefits, but, if the tool provides insights on how to make an organisation more sustainable overall, then organisations are likely to invest in it.

Interviewee I_1 began by mentioning that will always be a constraint for organisations. Larger enterprises tend to be more organised and dispose of standardised procedures that help them minimise errors and the time that is necessary to accomplish them, so the application of this tool in such a case would likely be leveraged. As long as organisations recognise the value this brings to their operations, the excessive amount of information and the time-consuming activities that are associated with its implementation will not be a critical issue.

Interviewee I_2 also agrees with the question. But to "translate the tool into the language of the organisation" is a more critical question than this one despite being correlated, since the adequation of the tool to the organisation's own internal standard procedures would make its implementation speedier.

Interviewee I_4 argues that the problem is not to obtain the data *per se*, but to guarantee the reliability of the information and if whether or not it is updated. As a suggestion, the interviewee indicated that the list of selected indicators should be kept short. However, this will always be a trade-off between time, resources, and comprehensiveness of the assessment.

Interviewee I_6 argues that the methodology for the implementation of Sustainability 4.0 is relatively simple, straightforward, and involves little bureaucracy, which is a plus. Additionally, the complexity of the analysis is directly correlated with the simplicity in obtaining the indicators. However, if there are some aspects that are not contemplated in the assessment, they will likely be the cause of trouble in the future, meaning that a complete and comprehensive assessment, despite being very time-consuming, may be beneficial and an investment that will ultimately payoff in terms of solving future problems and risk identification.

Interviewee I_7 agrees with the question but argues that this aspect can be mitigated if the indicator list could provide, upfront, information regarding where that information be could retrieved.

Overall, consensus regarding this matter was not attained. Whilst some interviewees argue that this is, not at all, a critical question since all comprehensive assessments take their time and tend to shift the issue of criticality to the phase where the selection of indicators is accomplished, others argue that this is, in fact, a critical aspect, since it was, more than once, pointed out as an argument by organisations so as to not implement these sorts of tools and also to justify why these tools ought to be implemented resorting to external consultancy services.

Q8 – Do you consider that the interconnectivity and possibility of measuring data in real time, which are some of the premises of industry 4.0, enables Sustainability 4.0 to become a tool that can be used to assess sustainability issues in real time, meaning end users can act upon it more quickly?

Interviewee A_2 thinks that this is not a critical issue and that in may not be, at all, useful. This is because all decisions that eventually arise from the application of Sustainability 4.0 do not take into account occasional and intermittent events but rather consider conjunctural ones, meaning that the priority of action are the events that occur on a frequent basis and can be, consequently, interpreted as a symptom of a greater problem. What would be effectively useful is the assurance of trustworthiness of the data that is collected, meaning that the end user of the tool knows for a fact that the data that is present in the dashboard is undoubtedly factual. For this reason, the inclusion of a metric that would assess the reliability of the data is a much more important feature to be a part of Sustainability 4.0 rather than the capability of measuring the data in real time.

Interviewee A_3 goes in the opposite direction as of the one followed by interviewee A_2, affirming that Sustainability 4.0 should, effectively, evolve into being fully integrated in the IoT and the cloud computing servers that support and allow this interconnectivity. In fact, the implementation of this tool in a given organisation should be thought through, as the potential of the tool is expected to grow exponentially with this feature.

Interviewee A_4 agrees that this would be a great feature of Sustainability 4.0 but demonstrated, simultaneously, a great amount of scepticism to its effective implementation because some indicators (*e.g.* degree of acceptance by local community) are impossible to be measured in real time. Therefore, this feature, if implemented, could only cover some of the indicators that had to have been, necessarily, widely validated by prior studies and research.

Interviewee A_5 also agrees that this would be very interesting to happen and would be the next logical step to take in the future, as it allows for the end user and decision-makers to act upon more rapidly.

Interviewee A_6 agrees with the question but stated this would only make sense in some indicators. The answer was similar to the one interviewee A_4 provided when stating that, despite being essential to track some indicators in real time, others are really not that necessary. The bottom line is that this feature depends on the nature of the indicator itself and its relative importance to the organisation.

Interviewee I_1 was peremptory in affirming that this feature would be "the best thing that could happen". However, it was mentioned that this is something that is very complex to achieve. What could be made in the meantime is to integrate Sustainability 4.0 with the already existing information systems and databases available in the organisation so that current value that is displayed is sure to be the most updated value.

Interviewee I_3 also agrees that it would make sense to take advantage of the possibilities that industry 4.0 provide, so to implement this would be absolutely desirable.

Interviewee I_6 states that this feature would add value, but two things need to be taken into account. Firstly, any decision that is taken based on the information grasped by the tool should not be taken into account right in the moment after the current value has reached a certain point where it would be considered a hotspot, meaning that decision-makers ought to look at conjunctural problems rather than punctual and timely-isolated issues. This argument falls in line with the opinion of interviewee A_2. Secondly, the possibility of having data measured in real time would be excellent to implement some sort of gamification strategies into the shop floor. This, in its turn, falls in line with the opinion of interviewee A_6.

Interviewee I_9 argues that a cost-benefit analysis should be taken into account in order to decide if the implementation of this feature is, indeed, beneficial.

Overall, consensus regarding this matter was, yet again, not attained. Whilst some interviewees argue that this is something that would add great value and would be the next logical step to take in further implementation stages, others argue that this doesn't make sense since decision-makers ought to look at conjunctural problems rather than punctual and timely-isolated issues. However, most of the interviewees pointed that that, if this were to be implemented, this would only make sense to be applied to some indicators.

Q9 – Imagine you were the chief sustainability officer of a given/your company and someone had handed you the user manual of Sustainability 4.0. Considering that the tool is customisable, what would you change in it?

Interviewee A_1 started by pointing out that the interviewee would begin by verifying if there were already any available and implemented systems that allowed the collection of data to be made more rapidly, allowing to cut some of the application time off. Likewise, any similarities between the organisation's own systems and Sustainability 4.0 (*e.g.* data from the human resource department's systems) should be taken into account so that the implementation of this tool could run smoother, meaning a conciliation between the new and old systems should be considered. Another key factor of Sustainability 4.0 is its flexibility and customisability, allowing end users to make the best of the tool according to their own managerial goals.

Interviewee A_2 started by affirming that, due to its background in the field of lean manufacturing, the interviewee would initially implement the tool with a very reduced number of indicators and with a narrower scope of application. Then, in subsequent stages, the list of indicators would increase as the scope grew wider according to internally set managerial goals. This attainable due to the modular nature of the tool. Here, the challenge is to increase the visibility of sustainability in a broader sense than just the economic dimension.

Interviewee A_3 reiterated that an effort should be made in diminishing the subjectivity associated to the choice of indicators. Additionally, the amount of data to be included in such an analysis should be reduced in order to underwhelm the analysis.

Interviewee A_4 states that the general framework of Sustainability 4.0 would remain unaltered. It was suggested the development of something that would resemble a catalogue of indicators from which the end user of the tool could retrieve the indicators to be present in the analysis, allowing to reduce its application time.

Interviewee A_5 reiterated that an effort should be made in developing a mobile app version of the tool. The focus should be directed to user experience and interface, and should come with a previously installed version of an indicator catalogue and/or database, allowing a step-by-step application, which would result in a reduction of the complexity of the analysis. This should be made prior to the application of the tool itself.

Interviewee A_6 argues that results should be displayed in the most graphical way possible, meaning the outputting figures and graphics that were to be present are to be quickly understood by everyone if it were to be used. This would also allow to introduce gamification into the shop floor, meaning that workers' performance could be tracked in real time and displayed to everyone in some sort of a ranking table, incentivising them to compete for the top spots, resulting in better performance levels, overall.

Interviewee I_1 provided a modular view on the indicator list, *i.e.*, the indicators present in the assessment can be added (or removed) according either to the needs of the organisation or to the widening of the scope of the assessment itself.

Interviewee I_2 began by stating the first customisation step would be the simplification of the indicator selection process. Then, the fact that indicators are not equally important would lead to the need of developing a weighted approach on the indicator level (which is different from considering a weighted approach to the three dimensions of sustainability).

Interviewee I_5 argues that the digital maturity should be assessed prior to the application of Sustainability 4.0. A digital maturity assessment is something that the organisation this interviewee belongs to has to offer as a solution and is employed to assess to what extent organisations are ready to make the shift to industry 4.0. This would allow to complement the assessment that Sustainability 4.0 has to offer.

Interviewee I_6 argues that there should be a dematerialisation of the tool, meaning that it should be implemented in a server in which all information was inputted, rather than in one single MS Excel® file that would be saved in one's computer. This slightly falls in line with what was mentioned by interviewee A_5. This would allow information to be inputted by any worker and would be made visible to anyone in the value chain. The methodology itself would remain unchanged as it is very straightforward. Additionally, the outputting SEP table should have some sort of a progression bar that tracked which actions have already been taken and which ones are yet to be taken.

Interviewee I_7 also argues that an effort should be made in taking advantage of the existing databases in order to streamline the process of collecting the indicators. This was very similar to what interviewee A_1 defended. The implementation would, therefore, run as smoothly as more linkages between Sustainability 4.0 and the existing monitoring systems exist. "Everything that can facilitate the process of collecting the necessary information in order to compute or obtain the indicators is absolutely critical".

Overall, interviewees mentioned that they would not change the methodology for the application of Sustainability 4.0 as it is very straightforward. However, most of the changes that were suggested were related to the step where the indicators to be present in such an assessment are selected.

Q10 – Should all three dimensions (economic, social, and environmental) have equal importance or should there be a weighted approach?

Interviewee A_1 considers that an egalitarian view of the three dimensions of sustainability, meaning that none of them is more important than the other, is the one organisations should take into account despite recognising that this is not the reality of the business world. In fact, organisations will not pay attention to the environmental and social dimensions until the economic one shows satisfactory results, meaning there is a clear primacy of this dimension.

Interviewee A_2 is peremptory in affirming that "a weighted approach of sustainability would be the worst thing that can ever been done to sustainability". The interviewee defends that no sustainability assessment tools should have weights. However, some indicators within the same dimension are more important than others (*e.g.* the reduction of cyanide discharges into the environment does not have the same impact as the reduction energy consumption). Therefore, a weighted approach on the indicator level is something that ought to be implemented.

Interviewee A_3 agrees will interviewees A_1 and A_2 when they mention an egalitarian view of the three dimensions of sustainability is the right approach. To operationalise a weighted approach on the three dimensions of sustainability would mean that a single score, *i.e.*, a number that would rank and classify the performance of the organisation as a whole, ought to be computed. This would lead, eventually, to the computation of mid-scores that would rank each dimension as a whole. This is not at all an easy task. However, this interviewee also showed openness towards the weighted approach on the indicator level rather than a dimension-wise one.

Interviewee A_4 indicates a preference for the egalitarian vision of sustainability, mentioning that the way Sustainability 4.0 carries out its assessment is the correct one in the light of this perspective. The implementation of a weighted approach in light of the three dimensions of sustainability would, itself, increase the complexity of the analysis, which can, alone, be sufficient reason for organisations not to make use of it.

Interviewee A_5 argues that this question would depend on the case it is being applied to. However, regardless of the decision, the possibility of providing a weighted assessment should be something to be implemented in the tool.

Interviewee I_1 personally believes all dimensions are equally important. However, the interviewee recognised that organisations start by looking onto the economic dimension and only when the sustainability of this dimension is assured, the social dimension is the one that will be considered next in the priority list.

Interviewee I_2 also agrees with interviewee I_1, stating a preference for this approach on sustainability. If any weighted approach was to be followed, it should be performed in a subsequent stage rather than in the application one.

Interviewee I_3 argues that the weighted approach would be the most advantageous to the eyes of decision-makers. It was suggested that there could be a tuning up of weights according to the needs of the decision-makers. This, however, would raise the obvious logical question of biased assessments, *i.e.*, the assessment would be skewed in such a way that would benefit the interest the decision-maker wanted all along and is not, in any given way, recommendable.

Interviewee I_4 believes that an egalitarian view should be the most desirable. However, the interviewee recognised that this is not something that effectively happens in the business would where the economic dimension takes the top spot. It was also mentioned that society also plays a major role in the definition of priorities. A perfect example of this is the increasing external pressures from societies to compel organisations (and policymakers) to be more sustainable.

Interviewee I_6 agrees that there should be a weighted approach but that the weights ought to be defined by the organisation itself. The tool should only provide a dashboard that is compatible with the tuning of the weights, updating the results according to the inputted weights.

Interviewee I_7 argues that a weighted approach on the indicator level would not only make absolute sense, but would also allow the organisation to segment its subsequent course of action by defining which hotspots are more critical, meaning that implementation success rates are likely to increase.

Interviewee I_9 argues that the weights that were to be assigned should be decided by all stakeholders rather than just the BoD or the end user of Sustainability 4.0. As to the assignment of weights to each of the indicators whilst maintaining the egalitarian view on the three dimensions of sustainability, the interviewee mentioned that this is already a reality in the organisation the interviewee belongs. This allows to prioritise the hotspots by order of importance. However, the interviewee mentioned that the process of assigning weights to the indicators is a subjective process made at an internal level.

Overall, interviewees from the academic dimension tend to argue that any assessment of sustainability should opt for an egalitarian view of its three dimensions, whereas interviewees from the business dimension tend to argue the opposite. However, there was a general consensus towards the fact that not all indicators are equally important and that the weighted approach should start by looking at the indicator level rather than the dimensional level.

Q11 – The final output of Sustainability 4.0 is the development of a stakeholder engagement plan. Do you think that all stakeholders will accept whichever changes that are proposed?

Interviewee A_1 considers the acceptance of changes by stakeholders to be something very difficult to attain and something which sees its difficultness increase as more stakeholders are considered in the assessment.

Interviewee A_2 states that, generally speaking, the stakeholders that are more likely to resist to any proposed changes are the workers and middle management. As the interviewee said, "the clients will like it, the suppliers will have to accept it, the local community will be thankful for it, and the workforce will simply follow the guidelines". In this case, the workforce will end up accepting the proposed changes since the fundamental point of applying Sustainability 4.0 is to track and improve sustainability standards which will, eventually, improve the working conditions. The problem resides in the top management level since these are the ones that will be the face of these changes as they are strategic changes. In case there is a great amount of resistance, the problem resides in the way top management decides to mitigate the hotpots and not in the tool itself.

Interviewee A_3 was much more sceptical towards this part. The interviewee believes that incentivising all stakeholders to embark in the same direction would be something extremely difficult to accomplish since they all have very distinctive and sometimes mutually exclusive objectives. This is, therefore and according to the interviewee's opinion, the trickiest part of the application of Sustainability 4.0.

Interviewee A_4 states that "it is obvious that they won't accept it". But this is a question to be resolved internally and at the top management level. It is uncorrelated with the way the tool itself is constructed.

Interviewee I_1 refers that this part of the tool falls into the field of change management, which is, in its turn, part of the field of project management. Professionals in this area would be best suited to conduct this part of the application process as their expertise would help to minimise any form of resistance.

Interviewee I_2 argues that, as long as all stakeholders are involved from the beginning of the implementation project and since it is meant to benefit them, resistance will be minimised.

Interviewee I_3 argues that this will, most likely, not be a problem, as most of the intervenient stakeholders "do not have a choice" other that accepting them.

Overall, interviewees from the academic dimension tend to find this aspect more troublesome than the ones from the business dimension. But it was agreed that it can be, depending on the subject, a critical aspect.

Q12 – How can the willingness to accept change by stakeholders be maximised?

Interviewee A_1 states that it is fundamental that all stakeholders feel involved in the process of hotspot mitigation/elimination. One thing that was mentioned is that organisations like to have several scenarios kept in reserve, meaning that the outputting SEP should comprise several actions for predetermined scenarios. This way, the organisation is prepared with backup actions that can be triggered whenever, for any given reason, some are not possible to perform. This led to the interviewee mentioning that using operations research methodologies to, effectively, maximise this acceptance. Multi-objective optimisation techniques are employed whenever optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objectives in which the benefit for each stakeholder is maximised and the cost of implementing that hotspot mitigation/elimination action is minimised (if desirable). In this scenario, a set of Pareto optimal solutions, meaning that none of the objective functions can be improved in value without degrading some of the other objective values, can be obtained (Ehrgott, 2005). This way, an optimum SEP, sustained by scientific methods can be obtained. Of course, this alone does not guarantee its forthright acceptance by all stakeholders. Another suggested method to maximise the acceptance of changes by all stakeholders is to employ the Delphi method. The Delphi method was developed by RAND, an institution that helps improve policy and decision-making through research and analysis, in the 1950s. It consists of gathering a group of experts who anonymously reply to questionnaires and subsequently receive feedback in the form of a statistical representation of the "group's response", after which the process repeats itself. The goal is to reduce the range of responses and attain something as close as possible to stakeholders' consensus (Helmer, 1967).

Interviewee A_2 reiterates that the maximisation of the acceptance of the proposed changes by all stakeholders depends on the performance of top managers. All stakeholders will embrace the challenge of implementing Sustainability 4.0 correctly because it is designed to contribute to the enhancement of all aspects of the everyday life of an organisations.

Interviewee A_3 argues that the key to guarantee the maximisation of the acceptance by stakeholders depends on presenting the outcomes as win-win situations. The interviewee also echoed the utilisation of operations research methods to accomplish this such as the ones suggested by interviewee A_1.

Interviewee A_4, in its turn, argues that the application of this tool is something from which everyone benefits from. The key to maximise the acceptance by stakeholders is to guarantee they are involved from the very beginning of the project. When asked to comment on interviewee's A_1 suggested use of operations research methods, this interviewee agreed that this is something that could be used and would be desirable but should not be the first thing to use. The criteria for the acceptance of any change is, simply, a positive answer to the question *Will my everyday life become better with this?*. As long as any proposed changes are presented as such, resistance to acceptance will not be a problem. One thing that was also mentioned is that organisations tend to like to have multiple scenarios of action, *i.e.*, a list of possible decisions to be taken for a single problem, corroborating interviewee A_1's statement.

Interviewee I_1 mentioned that the early-stage involvement of relevant stakeholders is key to maximise their acceptance to change and to minimise any form of resistance. This way, all stakeholders will feel like they were heard and were aware that the whole purpose of the application of Sustainability 4.0 was to highlight the hotspots of the system so that an action plan that benefits them can be developed.

Interviewee I_2 reiterates that, as long as stakeholders feel like they were heard and taken into account during the implementation process, resistance is likely not to be a problem.

Interviewee I_3 states that the acceptance of something always depends on the topic. As long as something is done to improve the stakeholders' life, it will likely be accepted. It was also mentioned that project managers would have to take part in the process of the application of Sustainability 4.0, as they are the most skilled personnel to handle these kinds of subjects.

Interviewee I_4 argues that this maximisation is achieved by making stakeholders conscious of the increase in competitiveness that result from the proposed actions, meaning that stakeholders should be aware of the overall benefit that will come as a result of taking such actions, especially in the long term.

Interviewee I_7 argues that decisions that are concerted between sectors/industries as a whole are much more likely to face minimal resistance in comparison to equivalent decisions made solely at the organisational level. Therefore, if decisions could be made in the context of a generation of a consensus, it would be beneficial.

Overall, interviewees believe that an early-stage involvement of stakeholders in the process of applying Sustainability 4.0 would ensure the minimisation of resistance to the proposed hotspot mitigation/elimination countermeasures. Additionally, other methods such as multi-objective optimisation techniques and the Delphi method were also proposed.

Q13 – Will Sustainability 4.0 contribute to the effective positioning of sustainability in a more central focus of any decision-making processes?

Interviewee A_1 assumes that sustainability will likely never take the central position of any decision-making processes. However, this tool, mainly due to its straightforwardness, namely in pointing out what is going well and what is going wrong, definitely helps decision-makers to be more aware of these questions and to have their decisions well-sustained.

Interviewee A_2 peremptorily affirmed that, as long as a researcher believes in the potential of what she/he has developed during the course of her/his work, then it has all it takes in order to succeed, meaning that if Sustainability 4.0 was designed to track sustainability performances in a given organisation and to provide decision-makers with solid information on which to sustain their decisions, then it has all it needs to thrive. It was also mentioned that the increasing awareness of societies towards the topic of sustainability, and the fact that they demand organisations to be more transparent and more sustainable represent a form of external pressure that contributes to foster the development of sustainable decision-making assistant tools such as the one Sustainability 4.0 is. Additionally, the fact that the development of these tools is being done prior to the full operationality of the fourth industrial revolution, which is still in its early stages, according to this interviewee, is nothing but an advantage, not only to organisations and decision-makers, but to society as a whole.

Interviewee A_3 firmly believes that this tool will help decision-makers to make more sustainable decisions and to make organisations more sustainable overall. However, the interviewee fears that, due to the fact that Sustainability 4.0 addresses the three dimensions of sustainability separately and independently, organisations may tend to use only the part in which the economic dimension of sustainability is assessed, disregarding the remaining two. However, it was mentioned that the customisability and flexibility, which are some of the key features of the tool, will definitely help organisations to consider sustainability into their operations since the tool can be adapted to their needs and reality. Sustainability 4.0 was, in fact, compared to an SAP system, which is commercialised as a standard package that ought to be customised according to the requirements of the company that decides to implement it. Another thing that was mentioned was the possibility of using Sustainability 4.0 as an inspection tool that could be used, for instance, by governmental agencies responsible for either law enforcement regarding environmental legislations or health and safety regulations so as to assess any infractions of the law. Despite having this potential, it was agreed that this should not be the correct application of the tool.

Interviewee A_4 argues that one of the main reasons that explain the fact that organisations don’t track their performance in terms of sustainability is that they don’t possess the means to accomplish it. The fact that Sustainability 4.0 is designed to effectively tackle this problem and does such in a simple manner with a framework that provides straightforwardness is bound to make organisations more willing to track their performance and act accordingly. What this tool manages to accomplish is to simplify the whole process of tracking sustainability performances which is something organisations consider to be a very complex task.

Interviewee A_5 states that, since this is the first tool that the interviewee had seen that delivered the purpose of assessing and tracking sustainability in an industry 4.0 context, it has all it takes to, at least, make a positive impact in that sense.

Interviewee A_6 agrees that, as long as the tool is correctly implemented, whether internally or resorting to external consultancy services, it definitely has the potential to provide decision-makers with solid information to make more sustainable decisions.

Interviewee I_1 goes in a similar direction to the one taken by interviewee A_4, stating that, as long as organisations have tools that serve the purpose of tracking their performance in terms of sustainability, they are likely to do it, and Sustainability 4.0 is perfectly capable of this task. If the tool provides decision-makers with sufficient information to make more sustainable decisions, then it has all it takes to deliver on that purpose.

Interviewee I_2 was sceptical about this fact. It will depend on the way it is presented to an organisation and the effort that is made in turning it saleable. It will not, however, be suitable to be applied in every organisation. When asked about the possibility of using Sustainability 4.0 as an inspection tool by governmental agencies, despite recognising it has that potential, the interviewee argued that this would not be the best use for it. However, the tool could be used to identify and reward organisations that employ the best sustainability practices in the field.

Interviewee I_3 argues that it is expected that this tool contributes to place sustainability in a more central position of the decision-making process since it is, by design, developed to accomplish that, precisely.

Interviewee I_4 agrees with the premise of the question. However, in a practical sense, decision-makers have very limited time to make sustained decisions as their job usually requires making quick decisions. The major driver for the development of scientific methods to sustain and to help attaining higher competitiveness levels is the amount of time a given operating scheme stays unchanged (*e.g.* in an automobile industry context, this would correspond to the time that a given car model is being manufactured and, therefore, the assembly line remains relatively unchanged during that period of time).

Interviewee I_5 "has no doubt that it will". In today's world, every decision has to take into account the fact that sustainability matters since it is the only way the organisation can sustain itself through the years.

Interviewee I_6 disagrees with the question. It is something that depends, ultimately, on the mentality of the organisation's BoD. As much as the tool offers the ability to empower decision-makers to make more sustainable decisions, whether or not they effectively make it will always depend on the views of the organisation toward this topic. However, the interviewee recognised its potential to be used as an inspection tool.

Interviewee I_7 argues that this would only be true if, using Sustainability 4.0 as an example, indicators could isolate the effects of the introduction of industry 4.0, meaning organisations would only use these tools if they could isolate the impacts that are prompted as a result of a specific organisational change.

Interviewee I_8 goes in the same direction as interviewee I_4 when mentioning that this will ultimately depend on the mindset of the managers of the organisation. But the fact alone that there are tools for the assessment of sustainability, in any context, is always a positive thing.

Interviewee I_9 agrees with the question because this tool accomplishes to organise information in a straightforward manner, empowering decision-makers to make decisions sustained in sound data.

Overall, interviewees agree that the creation of these sorts of tools are always beneficial and will contribute to place sustainability in a more central position of the decision-making process.

6.3. Chapter conclusions

This chapter covered the process of validating Sustainability 4.0. This follows the presentation of the step-by-step hands-on guide to apply the tool in an organisation. It was presented as a tool that has the ability to identify the hotspots of the system, *i.e.*, the aspects that have deteriorated of have failed to surpass the predetermined PRP upon the implementation of industry 4.0 technologies, setting the future course of action to present solutions on how to mitigate or, if and whenever possible, eliminate those exact hotspots.

In order to validate Sustainability 4.0, a two-stage process was employed. Firstly, a group of experts in the field were brought together in a focus group so as to provide initial feedback regarding the scientific validity of Sustainability 4.0. Then, in a subsequent stage, the version of Sustainability 4.0 that resulted from the previously conducted focus group was presented to fifteen experts in the field – six from the academic dimension and the remaining nine from the business dimension. These interviews allowed to assess the applicability of Sustainability 4.0 to a real-life context. From these interviews, a lot of information was generated. This part was covered in the previous section.

Overall, the interviewees' reaction and receptivity to Sustainability 4.0 was overpoweringly positive whilst considering it makes a very strong case for the acclamation of Sustainability 4.0 as a tool to assess sustainability impacts in a smart manufacturing context, despite, of course, some remarks having been suggested. Moreover, interviewees' general perception is that industry 4.0 will, undoubtedly, be the cause of impacts that will affect all dimensions of sustainability. Table 15 aims to summarise the main conclusions that were drawn from the interviews, as well as suggestions that were made, divided by aspect.

Table 15 – Summary of conclusions and suggestions collected from the interview process (source: author according to the interviewees' feedback)

Indicators	〉 Development of a comprehensive and collaborative sustainability indicator database for the context of industry 4.0 to minimise the necessary time for the indicator retrieval and selection phases; 〉 Development of a version of Sustainability 4.0 that resorted solely to GRI indicators and standards in order to assure the standardisation of the assessment and to ensure a solid comparison basis between organisations; 〉 Inclusion of a metric that would assess the reliability of the data that is collected in order to obtain and/or compute the indicators; 〉 Development of a methodology that would allow to rank indicators, within the same dimension, by importance, assigning weights to them; 〉 Assignment of each indicator to an indicator-owner, *i.e.*, a specific individual who would become responsible for its continuous measurement and for updating the dashboard with information regarding that specific indicator.

Further implementation stages	〉Dematerialisation of Sustainability 4.0, *i.e.*, implementation of the tool in a platform that can be accessible to all (*e.g.* server) rather than in one single file saved in one's computer and only accessible to some, allowing its continuous improvement and updating process; 〉Listing of which indicators are to be measured in real time and definition of how this real time measurement of data is to be attained from the technological point of view.
Engagement plan	〉Use of operations research techniques, namely multi-objective optimisation techniques, in order to obtain an optimal set of actions whose maximisation is assured; 〉Employment of the Delphi method to mediate any possible conflicts that may arise when defining the SEP in order to generate consensus within stakeholders.
Applicability	〉The application of the tool was considered to be dependent on the use of external consultancy services in order to ensure its correct application; 〉Conversion of Sustainability 4.0 into an inspection tool that would allow to identify organisations that don't comply with regulations; 〉The tool can be extrapolated outside the context of industry 4.0 and be applied in any process of organisational change, from any point A to any point B in time; 〉Conversion of Sustainability 4.0 into a dashboard that would allow to implement gamification strategies in the shop floor; 〉Use of Sustainability 4.0's framework in order to identify organisations whose practices in the field of sustainability are notorious to either award them or learn from the best-in-class; 〉Possibility of defining the PRP with a different value rather than the arithmetic average between the maximum and minimum values defined in the benchmarking section whilst maintaining the analogy of assigning 0% to the minimum value and 100% to the maximum value; 〉Development of a weighted approach of Sustainability 4.0, meaning the three dimensions of sustainability would become ranked; 〉Employment of Hoshin Kanri and Balanced Scorecard frameworks to guarantee the attainment of the project's objectives.

Like any other tool, Sustainability 4.0 has its limitations and hindrances – some of which were mentioned during the course of the interviewing process. The next chapter will shed some light over this subject, providing some suggestions to overcome them, as well as some closing and concluding remarks.

7. Final conclusions and future work outlook

This chapter briefly describes the work that has been heretofore presented whilst outlining its main conclusions. It additionally provides some future research outlooks and guidelines, empowering researchers to pursue further work in the field of sustainability within the context of industry 4.0.

The industrial fabrics of the world's most developed economies are becoming increasingly and successively more digital due to the democratisation and wide-spread diffusion of internet-based systems, creating the perfect ecosystem for another industrial revolution to occur. Industry 4.0 is, therefore, the current and ongoing trend in automated and interconnected systems, and also the climax of the three preceding industrial revolutions. These new technologies and consequent conjunctural transformations will change the relationships between employers and employees, business models pursued by organisations, and trigger new strains on both the environmental and social systems in which organisations are embedded. However, the conducted literature review stressed the lack of research regarding suitable and tailored sustainability indicators, assessment methodologies, and/or metrics for the introduction of these disruptive technologies on the shop floor level.

Whilst searching appropriate sustainability assessment metrics and methodologies for an industry 4.0 context, several indicators were found in the literature, building the basis for a comprehensive assessment of sustainability in all of its three dimensions. Additionally, one of the goals of this review was to empower individuals to embark in a critical discussion regarding their suitability to address the topic of sustainability in a smart manufacturing context.

As a result of this search process, there was a need to organise the information provided by the previously collected indicators in order to generate valuable knowledge on the extent the introduction of industry 4.0 technologies in the shop floor has influenced (or influences) a given organisation's sustainability patterns, as well as to transform this knowledge into inputs of subsequent decision-making processes. As such, the methodology for the development of a tool which allows to measure and track sustainability indicators, in each of its three dimensions and in an industry 4.0 context, was presented. This tool – **Sustainability 4.0** – starts by assessing, for each selected indicator, two values: a prior value and a current value, in a given case where the technological shift is considered to be complete; or the current value and a target value, if the application of this tool is being performed in the midst of that technological shift. This allows for the end user to identify what is going well and what is going wrong in this process. The hotspots of the systems, *i.e.*, the indicators whose figures have worsened or have failed to surpass the predetermined PRP, are to be mitigated (or, if and whenever possible, eliminated) through the development of a stakeholder engagement plan.

Following the conceptual development of this tool, there was a need to validate its scientific legitimacy, as well as its applicability to a real-life context. For this work in particular, the validation phase consisted in a two-stage procedure. Firstly, a preliminary version of Sustainability 4.0 was validated resorting to a focus group methodology. This focus group consisted in gathering a circumscribed group of experts in the fields of sustainability and industry 4.0 in a group interview to guarantee its scientific legitimacy. The discussion that was generated allowed to collect much precious feedback from all intervenient parties. This information was then transformed into consistent knowledge which allowed to finetune and consolidate Sustainability 4.0 into its pre-final version, *i.e.*, the one that is presented in the fifth chapter of this document.

Following the focus group validation methodology, another methodology – face-to-face in-depth interviews – was employed to further validate this tool, namely its applicability to a real-life context. As such, fifteen experts in the fields of sustainability assessment and industry 4.0 (six from the academic dimension and nine from the business dimension) were interviewed. These interviews allowed to collect relevant and diverse inputs which allowed to consolidate the tool. A wrap-up of the main topics that were brought up are presented in table 15.

Research in the field of sustainability *per se* is, fundamentally, an everlasting quest as societies evolve continuously. Furthermore, future prospects indicate that sustainability will be an even more relevant topic within policymakers and, in particular, European policymakers as the results of the 2019 European elections – which reinforced the will of EU citizens for members of the European Parliament to take clear action in this front – have substantiated. As to what research in the field of industry 4.0 *per se* is concerned, due to the novelty of this thematic, a lot is yet to be studied and, as industry 4.0 enters, effectively, in the shop floor, more consolidated data can be retrieved. However, and as suggested by one of the interviewees, this is the first industrial revolution in which much of the awareness, information, and knowledge that surround this topic is being generated even before its effective occurrence, *i.e.*, before industry 4.0 technologies are, *de facto*, implemented in the shop floor. These facts should motivate and empower both decision-makers and policymakers to take advantage of this generated knowledge so that this transition runs more smoothly and is performed in a more sustainable way. This is, precisely, one of the strongest reasons why the development of frameworks and tools – such as the one Sustainability 4.0 is – are crucial to ensure that exact smooth transition.

The aforementioned reasons provide sufficient and valid motives to pursue further research in the field of sustainability in the context of industry 4.0. In particular, despite the exposition and development of the building blocks of the tool, Sustainability 4.0 has yet so much unravelled potential. In fact, one key feature of Sustainability 4.0, which was pointed out in more than one interview is its suitability to assess and track sustainability standards in the context of any organisational modification or paradigm change, *i.e.*, from any point A to any point B in time. It would be extremely interesting to extrapolate this framework to other contexts of organisational change rather than just the case of the shift to industry 4.0. The key issue here is that Sustainability 4.0 is, by design, a tool to assist decision-making processes and that, despite the fact that it was indeed developed to assess the impacts that the implementation of industry 4.0 technologies prompt in the shop floor, it is also an undeniable fact that, due to its comparative and modular nature, it can be generalised to other circumstances. As such, the development of a tool that, despite having both similar guidelines and an analogous implementation methodology as Sustainability 4.0, could track and assess sustainability standards, and identify the system's hotspots, in any given context of organisational/paradigm change, would be very beneficial.

Another variation of Sustainability 4.0 that was mentioned by most of the interviewees from the business dimension is the development of a weighted approach on the assessment, whether at the indicator level, *i.e.*, in the same dimension, some indicators are more important than others; or at the dimensional level, *i.e.*, the three dimensions of sustainability become prioritised. To develop such a tool that provided an adjustable dashboard that could, for instance, update the results in real-time as the weights of the indicators and/or the dimensions were inputted, would be of great value, especially to compare and prioritise actions since the identified hotspots would be ranked by order of importance.

In chapters 4 and 5, it is mentioned that one of the contexts for the application of this tool is in a case where the process of implementation of industry 4.0 in an organisation is considered to be complete (context A). Effectively, this raises several questions:

To what extent has the organisation adopted industry 4.0 technologies in their operations?
What defines a complete implementation of industry 4.0?

One way to answer to these questions is with some sort of a digitalisation index. The aforementioned DESI index measures the extent of digitalisation of each EU country, being, for that reason, a mostly macroeconomic indicator. The literature review highlighted that there are, to this date, no records of a standardised, well-established and widely acknowledged indicator to assess, precisely, the degree of digitalisation or the extent of industry 4.0 implementation a given organisation has attained, *i.e.*, a microeconomic analogous to the DESI index. The development of such an index would contribute to enrich Sustainability 4.0 and remove some subjectivity off the table, as the results provided by the indicators could be correlated with this value, allowing a much more comprehensive assessment.

Despite the vertical and horizontal integrations which are some of the premises of industry 4.0, one limitation of the tool, if considered to be applied in the context of industry 4.0, is that it merely focuses on the shop floor level and the organisations' operations rather than the supply or value chain as a whole, which, naturally, restricts the scope of the assessment. This comes as a direct inheritance of the characteristics of industry 4.0, since these technologies are focused, precisely, on the shop floor level. However, an assessment of sustainability in the supply chain as a whole, rather than in just one echelon, adds much more value to all intervenient entities. As such, a version of Sustainability 4.0 with a scope of assessment wide enough to encompass the whole value chain, resorting to the premise of data centralisation, should also be developed.

In Portugal, the attribution of EU funds to help SMEs to invest in making the shift to industry 4.0 in their operations is currently made by a government-regulated programme (Portugal 2020). In order for organisations to apply to these funds, they ought to comply with numerous guidelines and, even after their application having been successful, the results need to be evaluated by frequent audits. As validated by several interviewees, this tool could be used as an inspection tool by governmental entities such as the Authority for Work Conditions, the Portuguese Environmental Agency, or even the Portugal 2020 programme, to check whether or not the organisation complies with existing regulations or if the funds are being efficiently and effectively employed.

Another thing that was mentioned in more than one interview was the development of a skeuomorphic software version of Sustainability 4.0 that could route users through the step-by-step process of its application, allowing to decrease hypothetical training times. Additionally, this software version should be equipped with a comprehensive sustainability indicator database from which end users could select the indicators that ought to be present in the assessment, alongside with information on how to obtain and/or compute a given indicator. This software version should also promote the centralisation and accessibility of the information, meaning that anyone should be able to consult or update it whenever deemed necessary.

Finally, the last presented suggestion for further research work is the real-life application of Sustainability 4.0. Despite having been validated with fifteen interviews with a very diverse panel of experts, only a case study approach would offer the best results in order to determine whether this tool is applicable in an organisation and its consequent viability. Additionally, an effort should be made in transforming this tool in a way that it is more sellable and marketable. As suggested by most of the interviewees, the application of this tool in an organisation is more likely to be successful through the use of external consultancy services. Organisations would only hire these services if they saw and understood the full potential of the tool. Therefore, to market Sustainability 4.0 as a comprehensive and straightforward decision-making tool should be a logical step to take.

The topics of sustainability and industry 4.0 are, undoubtedly, intimately related, as this work demonstrated. Making the shift to industry 4.0 will impact each of the three dimensions of sustainability in different extents. Whether those impacts are mostly negative or predominantly positive is up to decision-makers and policymakers, but if they possess decision-aiding tools, *i.e.*, tools that provide them with solid and trustworthy information on which they can sustain their decisions, this will empower them to make better decisions. As such, the ultimate goal of this work is to provide decision-makers and policymakers with a tool for the assessment of sustainability in industries that have implemented (or are in the process of implementing) industry 4.0 technologies. With this, the topic of sustainability, in all of its three dimensions, might finally take a prominent spot in any policymaking and decision-making processes that take place.

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Appendixes

Table A1 – Interview script with the questions asked during the interviews (source: author)

Q1	Do you think that industry 4.0 will allow organisations to achieve more sustainability standards?
Q2	Which dimension of sustainability (economic, social, or environmental) will be most affected, either positive or negatively, from the implementation of these technologies?
Q3	Do organisations, when implementing such technologies, take into account the possible impacts that may arise in terms of sustainability? / Did your company, when implementing such technologies, take into account the possible impacts that may have arisen in terms of sustainability?
Q4	Do you think that Sustainability 4.0 will be useful to assess whether the implementation of industry 4.0 related technologies within organisations was made/is being made in a sustainable way?
Q5	Do you believe that organisations are willing to use this tool to assess whether this technological shift was made/is being done in a sustainable manner?
Q6	Do you think the application of this tool to a real-life context is feasible?
Q7	Do you think that the large amount of data that is necessary for a comprehensive analysis may hinder its application?
Q8	Do you consider that the interconnectivity and possibility of measuring data in real time, which are some of the premises of industry 4.0, enables Sustainability 4.0 to become a tool that can be used to assess sustainability issues in real time, meaning end users can act upon it more quickly?
Q9	Imagine you were the chief sustainability officer of a given/your company and someone had handed you the user manual of Sustainability 4.0. Considering that the tool is customisable, what would you change in it?
Q10	Should all three dimensions (economic, social, and environmental) have equal importance or should there be a weighted approach?
Q11	The final output of Sustainability 4.0 is the development of a stakeholder engagement plan. Do you think that all stakeholders will accept whichever changes that are proposed?
Q12	How can the willingness to accept change by stakeholders be maximised?
Q13	Will Sustainability 4.0 contribute to the effective positioning of sustainability in a more central focus of any decision-making processes?