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Steffen G. Scholz
Robert J. Howlett
Rossi Setchi *Editors*

Sustainable Design and Manufacturing 2023

Proceedings of the 10th International Conference on Sustainable Design and Manufacturing (KES-SDM 2023)

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Steffen G. Scholz · Robert J. Howlett · Rossi Setchi
Editors

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Preface

Manufacturing industries often consume substantial amounts of resources and energy, leading to pollution, waste generation, and the exhaustion of natural resources. Sustainable practices help mitigate them through minimizing resource consumption, reducing emissions, complying with regulations, enhancing operational efficiency, driving innovation, ensuring long-term viability, and promoting responsible waste management. It is a fundamental shift toward a more ethical, responsible, and resilient approach to robust industrial practices.

Within this context, the SDM-23 event presents an exclusive platform encompassing keynote talks, oral discussions, general tracks, and special invited sessions concerning the thematic realm of ‘sustainable design and manufacturing.’ These interactions foster the exchange of knowledge and the development of innovative concepts and practices. On behalf of both myself and KES International, I extend a cordial welcome to all those participating in this volume, encapsulating the proceedings of the 10th KES International Conference on *Sustainable Design and Manufacturing (SDM-23)*. This conference, composed by KES International, transpired from the 18th to the 20th of September 2023 in Bari, Italy.

The SDM conferences have consistently attracted exceptional contributions, a sentiment for which we extend our heartfelt appreciation. It is so encouraging to observe the influx of new contributors embracing SDM-23. We extend our invitation to all, fostering the aspiration that you will become integral assets of the expanding community of academics committed to pioneering sustainability research. Your contributions will assuredly enrich the orchestrating of forthcoming conferences.

This physical congregation served as an exemplary podium for showcasing the cutting-edge research and nurturing profound scientific dialogues encompassing sustainability in design alongside the advancement of sustainable products and processes facilitated by modern manufacturing techniques. The scope of applications encompassed every facet of the product lifecycle, design methods, the complete process chain, as well as modeling, simulations, and end-of-life evaluations. This comprehensive approach highlights the unwavering commitment to holistic sustainable production.

Building upon the accomplishments of its precursors, the conference prolongs the legacy of the preceding nine editions, sequentially hosted by Cardiff University, Wales, UK (2014); University of Seville, Spain (2015); University of Crete, Greece (2016); University of Bologna, Italy (2017); Griffith University, Gold Coast, Australia (2018); University of York, York, UK (2019); alongside the virtual editions conducted during the COVID-19 crisis (2020 & 2021), before the last event in Split, Croatia in September 2022.

Once again, the conference preserved an array of diverse tracks helmed by esteemed experts in disciplines including sustainable design, innovation, and services; sustainable manufacturing processes and technology; sustainable manufacturing systems and enterprises; decision support for sustainability; and Industry 4.0 and intelligent manufacturing. Our profound gratitude is extended to our program committee members, track chairs, promotors of special sessions, authors, and reviewers. Their continuous dedication ensured that the caliber of submissions, revisions, and acceptances for SDM-23 aligned impeccably with the exacting standards prescribed by Springer Nature proceedings.

Bari, Italy

Prof. Steffen G. Scholz
General Programme Chairs

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Chapter 1
A Simple Method for Implementation of a Solar Oven for Lumber Drying

Pedro Escudero-Villa, Alfredo Pachacama, Jéssica Núñez-Sánchez, and Liliana Topón-Visarrea

Abstract In Ecuador, the small and medium-sized wood industries dedicated to the manufacture of boards use a form of natural drying, which takes six months to two years depending on the moisture content, the type of wood, and the thickness. In regular bases, the natural drying process requires six months to obtain dry wood that can be processed to final products, which causes delays in the delivery of production batches and loss of time, affecting the internal economy. In this work, we present a design for a simple implementation of a solar oven to dry wood and derivatives. For this objective, we included the oven chamber physical dimensioning, the requirements and thermodynamic analysis, and a comparison with the standard traditional method. The oven was dimensioned to keep a range of temperature from 15 to 45° in a chamber of 42 m^3. The result of this design allows a time saving of 66.67% and profits of 304% per month for a standard wood processed. These results are possible due to the specific geographical location and climate of Ecuador, which directly influence the effectiveness of a solar oven.

1.1 Introduction

The state policies and requirements for the use of wood are increasingly controlled in the environmental issue; due to this a permit must be obtained from the Ministry of the Environment that allows the felling of forests [1], determining if the forest is suitable for harvesting, exploitation and thus not generate greater environmental impact [2]. In Ecuador, the industry dedicated to the extraction of wood and related activities is called forestry. According to indicators from the Central Bank of Ecuador (BCE), the

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timber industry has been growing over the years, ranking 17th out of 47th industries nationwide, contributing $1364.5 million dollars in 2018, 3% of the Gross Domestic Product (GDP) and an average interannual variation rate of 7.5% between 2009 and 2018 [3, 4]. In 2018, 67.1% of the Gross Value Added (VAB) of this industry was generated by the coast areas (Esmeraldas, Los Ríos), and mountains areas (Cotopaxi, Pichincha, and Chimborazo) [5, 6], and Amazon region [7].

The growing trend in prices worldwide makes it increasingly sustainable and justifiable to carry out the artificial drying of wood. There are species that are refractory to drying and must be dried slowly, such as Eucalyptus, which is why it is increasingly essential for the wood industry to improve drying processes [8, 9]. Production and trade of both pulpwood and sawn wood grew by 2% worldwide in 2018 reaching a record level of 66 million tons, respectively [10, 11].

Currently, there is a lack of dry material for sale and for the manufacture of boards used in formwork, pallets, furniture manufacturing, and other items [12, 13]. Therefore, it is necessary to design an efficient wood drying line that allows obtaining a variety of products and offering more stock to customers [14]. The natural drying process is a complex activity that involves aspects that directly affect production, such as the degree of moisture in the wood (20–30%) and the drying time required to reach the appropriate level of workability. Due to this, artificial drying constitutes the only alternative to meet the demands of the international market. An example is kiln drying that maintains controlled temperature, humidity, and air circulation in and around the wood, providing a higher quality product, removing about 93% of the moisture in the wood, thereby that makes the wood better quality to create furniture [14, 15].

In order for wood to be considered an optimal material for use, it must contain a percentage of moisture close to the hygroscopic equilibrium, that is, the moisture of the wood must be in accordance with two factors: humidity content and ambient temperature. This technical and adequate percentage has been established internationally at 12% humidity content (HC).

The objective of this work is to give an alternative option for a fast and efficient implementation of a controlled solar oven using engineering and automation tools to reduce the processing time in the manufacture of boards focused on the reduction of moisture in the final product.

1.2 Materials and Methods

The solar oven design has two parts, the oven chamber, and the control system. The procedure for the solar oven design includes the characteristics of raw material, and preparation, the description of the traditional method for natural drying, and the solar oven design.

Fig. 1.1 Obtaining and treatment of raw material. **a** Felling and Storage. **b** Cutting boards. **c** Stacking for drying

1.2.1 Raw Material

The eucalyptus (Eucalyptus globulus) was used as raw material to obtain boards. This species has a density of 730 Kg/m^3, and a volume of $Vm = 6m^3$. The material was extracted from a local forest through felling that is approved under a license from the Ministry of the Environment. The pieces of material were prepared with a constant length of 2.5 m, and a bench of 15 cm wide. Subsequently, the boards were cut giving a dimension of 25 mm thickness (Fig. 1.1).

1.2.2 Natural Drying of Wood

It refers to the decrease in humidity of products or materials in natural conditions exposed to direct solar radiation. In this process, factors such as air humidity, wind speed, and direct or indirect solar energy are critical variables to determine the speed of process including the final quality of the product. The disadvantages of the natural wood drying process are long drying times (from 4 to 6 months or more to achieve efficient drying, depending on the type of wood). Cracks also occur and drying is not uniform. Six months are considered a standard time for this process (Fig. 1.2).

The natural drying is a critical process due to it depends directly for the climate conditions.

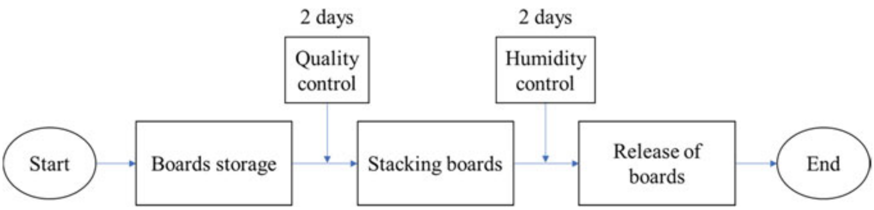

Fig. 1.2 Flowchart of the natural drying process

1.2.3 *Dryer Design*

The design of the solar oven was defined the working conditions. The basic requirements include the chamber capacity, the range of working temperature, and the control of internal humidity. Furthermore, it was crucial to consider the geographical context. In this case, the study was carried out in Ecuador, more precisely in the province of Pichincha (−0.329151, −78.487850), which is characterized by a high-altitude (2500 masl.) and subtropical climate. The temperatures typically ranged from 10 to 25 °C, accompanied by an average relative humidity of 70–80%. Due to its location along the equator, the region benefited from constant sunlight exposure [16].

Size and Capacity of the Solar Dryer

It is considered that the optimal size of the chamber is a function of the volume of wood to be dried, it is not convenient to build ovens with capacities greater than 15 m^3, because the efficiency decays while increase de the chamber size. The width of the dryer ensures uniformity in the circulation of air through the wood pile. Therefore, the dryer should not exceed 5 m in width and length. According to theses specifications, the solar oven dimensions were defined for 3.5 m wide, and 3.5 m long, with a maximum height of 3 m, allowing stacking a load of wood of 6.6 m^3.

To obtain a correct air movement and uniform drying was calculated a ratio between the volume of the chamber (Vc) and the volume of the wood (Vm). ratio = $\frac{\mathrm{Vc}}{\mathrm{Vm}}$. For a ratio = 7, the chamber volume was Vc = 42 m^3 [1].

Parameters and Thermodynamic Calculations

It was necessary to analyze the heat transfer and thermodynamic of the chamber. Following the natural characteristics of the raw material to be dried was considered a minimum amount of wood (1 m^3). The total heat needed for each m^3 of wood (Q) is defined by $Q = q.W_t$, where q is the specific heat consumption and W_t is the total moisture to be extracted per m^3 of wood, obtaining a $Q = 454023.12\,\mathrm{kJ/m^3}$ of wood.

The specific heat consumption is given by $q = \left(I_f - I_o\right)/\left(X_f - X_o\right)$, where $I_f - I_o$ is the difference between final and initial enthalpy, $X_f - X_o$ is the difference between final and initial moisture content. The calculated specific heat is $q = 3183\,\mathrm{kJ/kg}$ for humidity. The initial and final enthalpies were calculated using Eq. 1.1.

$$\boldsymbol{h = CpT + w * hg} \tag{1.1}$$

where Cp is the specific heat at constant pressure, T is the temperature in °K, w is the specific air humidity, and hg is the saturated steam (Table 1.1).

Table 1.1 Enthalpies and moisture content

Parameters	Values
Initial enthalpy	40.34 kJ/kg of dry air
Final enthalpy	203.31 kJ/kg of dry air
Initial moisture content	0.0100 kg of humidity/kg of dry air
Final moisture content	0.0612 kg of humidity/kg of dry air

Control System

The control system was programmed by using an Arduino Uno platform, temperature, and relative humidity sensor DHT11, an LCD 16 $\times$ 2 display, and passive elements. The schematics is displayed in Fig. 1.3.

A boost exhaust fan was used for a best distribution of head inside the chamber. The automated control of the drying oven has a temperature and relative humidity meter that allows the control its ranges and keep track of the conditions that occur inside the dryer during the process.

The relative humidity is in the range of 65–75%. The Arduino board sends a signal when the temperature drops under 65%, sending a signal for the vents to be closed and thus again the humidity increases. When the humidity exceeds 75% the vents open, then the humidity decreases keeping the range controlled. The operation of the system was programming to keep the humidity in a defined range, controlling the vents and the activation of the fan working for 24 h continuously depending directly

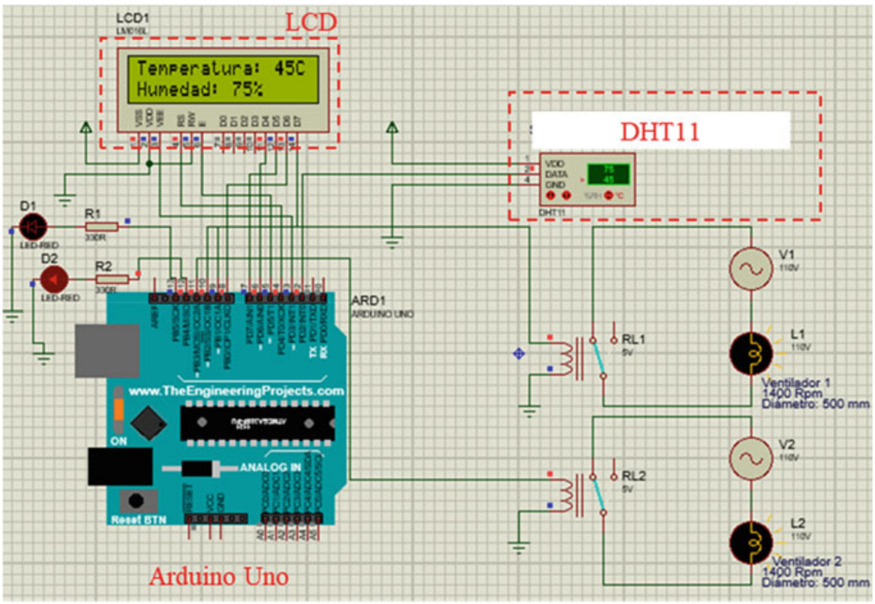

Fig. 1.3 Electronic system of the drying oven

on the temperature and humidity conditions emitted by the sensor. Usually, the fans will be activated in the morning when 45 °C is reached and will be automatically deactivated in the afternoon when this temperature decreases below 45 °C. The warning signs of the humidity ranges will be constantly activated since at night, the vents are closed, and the humidity increases.

1.3 Results and Discussion

As a first step, the wood was pre-drying for at least 30 days, then the boards were placed inside the oven. The oven was close hermetically. In the course of the day, the temperature varies consecutively which gives way to the operation of the fans. The dryer extracts the hot air generated in the collector, through the two fans to introduce it into the drying chamber, where it is directed toward the pieces of wood placed inside, forcing it to pass through them.

The dryer vents control the circulation of air inside the chamber; when kept closed, there is an internal recirculation because the hot air passes from the collector to the wood and from the wood to the collector heating up repeatedly. If they are kept open, the hot air will pass from the collector to the wood, and then exit directly through vents, thus introducing air from the environment into the collector.

The best distribution of solar energy inside the dryer occurs during the day, the longitudinal axis of the chamber is in a North–South direction. With these values the catchment area of the dryer will be 14 m^2, 3.5 m width, and 4 m length. To validate the solar drying system, measurements are taken of the temperature and humidity inside the oven. The weight of the wood is also recorded before and after the drying process and compared with conventional drying methods. Figure 1.4 shows the structure of the artificial dryer oven.

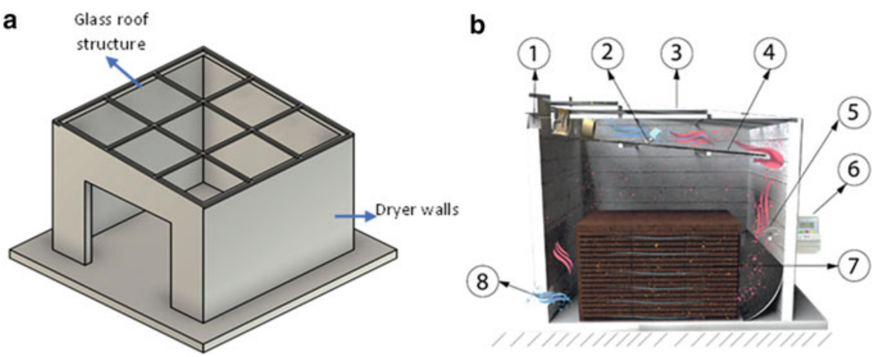

Fig. 1.4 Drying oven configuration. **a** Drying oven structure. **b** Drying oven parts: (1) fan, (2) temperature sensor, (3) glass roof, (4) solar absorption metal plate, (5) humidity sensor, (6) automatic control box, (7) wood to be dried, (8) air exhaust vents

Table 1.2 Record of estimated time of drying wood in solar oven

# Months	% HC	Process duration (days)
1	30	30
2	12	25
	Total	55

1.3.1 Natural Drying and Oven Drying Comparison

Table 1.2 gives the results of wood drying time in the solar oven, taking into account that for the thermodynamic calculation, the month and day with the least solar radiation between 2020 and the first half of 2021 is considered so that the drying time is more accurate with respect to solar radiation, since atmospheric data are variable at different times of the year.

The design was considered a variation in the final temperature to determine the Total Hourly Energy gained by the solar heater, and it can be observed that the lowest humidity reached after 30 days is 30%; through thermodynamic calculation, it is determined that the drying time in the solar oven with the local climatic conditions was needed 25 days to reach a humidity of 12%.

The design of the drying line starts from the air pre-drying to reduce the humidity until 30%, this process takes 30 days. To this process was added 25 days of baked drying, resulting in 55 days of the whole process.

The first month lasts 30 days of natural drying, the second month refers to oven drying with a duration of 25 days. The standard time set for drying wood naturally was approximately six months. Table 1.3 demonstrates that the drying time for wood using a solar oven has been reduced to 55 days through the implementation of artificial drying. This adjustment is based on thermodynamic calculations that determine the optimal duration required to achieve the ideal moisture content for the wood to be workable.

Comparing the two methods, we identified the difference of monetary values for the two methods of drying. A reduced time is the principal advantage of the solar oven method for drying. The values estimated contributed to identify an improvement of 304% in comparison with natural drying. Figure 1.5 indicates the analysis of the decreasing slope for the moisture content. With these references, it is possible to identify the difference between semesters and make a comparison of them. The semester with the lowest moisture content after pre-drying was the second semester, as it coincided with the months of June and July, when there was a greater wind flow and solar radiation due to the summer season. According to Fig. 5a, after six months,

Table 1.3 Air drying and oven drying monetary values comparison

Type of drying	Total sale price	Process costs	Total profit	Time (months)
Air drying	1500	879.88	620.12	6
Oven drying	1750	1121.67	628.33	2

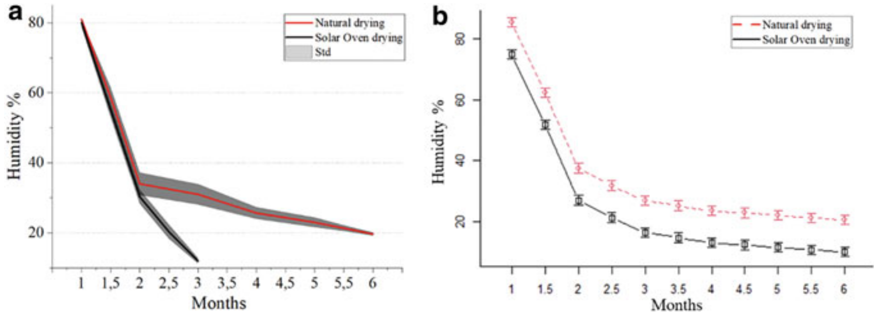

Fig. 1.5 Comparison between the natural drying process and solar oven drying. **a** HC versus time observations. **b** ANOVA graph

the humidity decreased to 20 ± 2% for natural drying, whereas for solar oven drying, the humidity dropped to 30% by the end of 30 days and reached 12 ± 2% by the 55th day.

Through an ANOVA analysis Fig. 5b, the differences between natural air drying and solar oven drying were confirmed. Differences in moisture removal times were identified. It was concluded that starting from the second month, the wood had completed the drying process, as the moisture content (HC%) reached the optimal level.

The design of a solar oven for drying wood was specifically tailored to adapt to the environmental and commercial conditions of Ecuador, thus providing unique value to this proposal. Similar works have been published about the analysis of heat exchange in a solar oven system with concentrated collector, providing useful insights for improving heat transfer efficiency [17]. Similarly, [18] was conducted an analysis of the performance of a solar oven and the impact of reflectors on solar radiation incident on the collector, offering strategies to enhance oven efficiency. Furthermore, the theoretically absorbed thermal energy by water is estimated, thus evaluating the oven's efficiency.

Our study brings a fresh perspective to the field by integrating a specific focus on local conditions and natural drying processes in assessing the performance and efficiency of solar ovens for wood drying. However, we acknowledge the dependence on climatic conditions as a limitation. Despite this, the significant improvement in efficiency of 304% that we achieved, compared to natural drying, and the inherent sustainability of our proposal mark a significant advancement in this research field.

1.4 Conclusions

In this work, we present a simple method for implementation of a solar oven for lumber drying with the objective to gives alternatives tools for the improvement of lumber industry in Ecuador. This way was proposed a physical design of a solar oven taking in account the characteristics of the raw material, and the maximum capacity of the oven chamber. A thermodynamic analysis was done to according to the oven chamber capacity and the characteristically needs for an effective drying. For the needs, identification was used the historical records of moisture content in boards using the natural drying. We identified the drying process time of 6 months for 500 Eucalyptus boards (6 m^3) using this tradition method.

The thermodynamics analysis allow us to obtain a chamber volume of 42 m^3 (width 3.5 m, length 4 m, height 3 m), and a catchment area of 14 m^2, as an optimal design. The monitoring system allows the reading of parameter for controlling the drying process through the reading of temperature and humidity level inside the chamber through the sensors. The result of the complete system allows us to reduce the drying time of wood by 66.67%, and profits of 304% per month for the standard wood processed.

Our proposal aimed to contribute to the improvement of traditional wood drying methods used in the region and provided the opportunity to replicate the design in locations with similar geographical conditions. The design offered a sustainable method to optimize the drying process while maintaining product quality.

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Chapter 2
Supporting the Transformation of Sustainable Business Models and Ecosystems—Progress and Opportunities

Cadence Hsien and Steve Evans

Abstract Corporations are under increasing pressure to be environmentally sustainable. As sustainability is complex and effects span across supply chains and industries, companies need to look beyond their organizational boundaries to tackle sustainability. To deliver transformative change for sustainability, companies can benefit from working with partners and stakeholders at the business ecosystem (BE) level. To this end, literature in sustainable business model (SBM) and in sustainable business ecosystem (SBE) can inform companies and their BEs in their sustainability transformation process. However, there is limited research on the perspective that integrates the changing nature of SBMs and SBEs. To address this, this study aims to provide an overview of the progress in these topics and develop a description of the landscape of tools that support companies' SBM innovation with a BE perspective by analyzing their roles and approaches. Through this understanding, insights can be gained to support future development and advancements for researchers and practitioners.

2.1 Introduction

Sustainability is placed at the top of the global agenda as reducing carbon emissions, managing resource scarcity, and being resilient emerge as critical goals amidst supply chain disruptions and increasingly extreme weather in the past years [1]. Both academics and practitioners agree that companies play an important role to support the transition toward sustainability [2, 3]. To do so, companies need to do more than

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simply comply with regulations and engage in corporate social responsibility [2] and need to integrate sustainability into their core business [4].

At a firm-level, this can be done by adopting technological innovation that support ecological sustainability [2], and implementing sustainable business practices like ecoefficiency [5] and ecodesign [6]. However, ecoefficiency and ecodesign practices, despite having reduced resource intensity and emissions [7], are not sufficient to offset the impact of industrial growth [8]. Rather, firms can drive more impact by taking part in SBM innovation by aligning the interest of all stakeholders, including that of the environment and society [8, 9].

Beyond firm-level approaches, system-level approaches are required as companies are positioned within a larger value network [10, 11] and have to work with multiple stakeholders to create sustainable value that they cannot create by themselves [12, 13]. Examples are industrial symbiosis and circular economy. Such approaches require working with multiple stakeholders related to a firm's BE. Here, literature around BE has been developed to support companies in developing strategies to manage their BE and their position within it [14–17]. However, BE research to support sustainability is nascent with limited studies on SBE. Therefore, there is a gap in supporting companies as they navigate toward sustainability while changing their BM within their BE.

To address this gap, this study will provide an overview of the progress in these topics and aims to develop a description of the landscape of tools that support companies' SBM in an SBE by analyzing their roles and approaches and identifying opportunities for future research. This will be done by reviewing representative literature in BM, SBM, BE, and SBE to track key themes emerging in this research and analyzing the tools developed to support practitioners in SBM and SBE.

2.2 Business Models

2.2.1 An Overview of Business Models (BM)

Early works in BM research started with an economic angle describing models for profit generation and progressed to include structural configuration of a business at the operational level and strategic aspects with directions for market positioning and growth opportunities [18]. The BM has since developed into a unit of analysis centered on a focal firm operating in a wider value network [11]. The general agreement is that a BM describes how a firm conducts business, deliver and capture value, and is a source of competitive advantage [19–21]. Today, BM research supports business and entrepreneurial managers by highlighting the importance of BM design to overall business success and developed tools and processes to support BM design and innovation [22].

Several researchers have called for businesses to innovate beyond traditional research and development, and use BMs as a form of innovation and competitive advantage [19, 23, 24], terming the process BM innovation. A popular tool for BM innovation is the BM canvas developed by Osterwalder and Pigneur [25] that helps to map and analyze BMs. To support practitioners, researchers have also developed processes to guide BM innovation [26–28]. These phased processes move beyond BM ideation and design and includes experimenting and implementing the BM.

2.2.2 Sustainable Business Models (SBM)

Within BM research, a stream of research is SBM. Referencing the BM framework, SBMs researchers pointed out the need to adopt a multi-stakeholder view, including the environment and society, of value to support sustainable value proposition design [22].

Increasingly, researchers are also describing circular BM, which adopts circular economy strategies like close, slow, intensity, dematerialize, and narrow resource loops [29, 30]. Within this research, the concept of ecosystem for circular BM is starting to emerge [31]. Here, researchers have highlighted that the implementation of circular BM is not a matter of a single company but influences other organizations in the ecosystem [32]. Others asserted the need for companies to work with diverse actors from different industries to close the loop [31] and adopt an ecosystem view to implement circular BMs [12, 31–34].

To support companies to change their BMs toward a SBM, researchers have developed tools to support sustainable and circular BM innovation [28, 35–41] and a detailed review of tools and approaches for sustainable and circular BM innovation have been compiled by Pieroni et al. [42]. A common theme is the need to consider multiple stakeholders as a company innovates its BM for sustainability [22]. However, findings by Pieroni et al. [42] conclude that despite the multi-stakeholder perspective taken, majority of the tools focused on the focal company's organizational boundaries despite the importance for inter-organizational collaboration for sustainability.

2.3 Business Ecosystem

2.3.1 An Overview of Business Ecosystem (BE)

The concept of BE has been gaining popularity in academia and industry [43–45]. The classic definition by Moore [17] describes the coevolution of companies in the BE around new innovation, while the modern definition describes the alignment among actors in the BE to materialize a value proposition [14] considering complementarities [44]. Coevolution occurs by integrating complementary innovations from members across the ecosystem and firms' coevolution results in the BE evolving across lifecycle stages of birth, expansion, leadership, and self-renewal [46]. To do so companies need to align their visions and coordinate their efforts and resources to ensure that their investments are aligned, and outcomes of their investments are synergistic for the ecosystem [46]. In addition to innovation alignment, Adner [14] also emphasizes the importance of aligning motives, incentives, and activities undertaken in the BE. Amidst this discussion, a consensus is that BEs are especially relevant to the pace of innovation today, where companies need to collaborate with ecosystem members to create and deliver value that they cannot fulfill by themselves and that the members of an ecosystem are interdependent [47, 48].

Recently, several scholars [49] note that the aspect of coevolution has largely been ignored by ecosystem researchers and re-emphasized how the concept of coevolution described by Moore [46] can be used to understand the emergence and management of value proposition [14] described in modern definitions of BEs [49].

2.3.2 Sustainable Business Ecosystem (SBE)

Similar to how companies work together in BEs to create and deliver value they cannot otherwise deliver by themselves, companies need to work together to create and deliver sustainability value that an individual company cannot deliver by themselves [12, 13]. Hsieh et al. [50] published the first case of a SBE in the form of a BE for a glass recycling circular economy. The authors adopted Moore's [17] ecosystem lifecycle stages in their study and described how a glass recycling ecosystem developed over time from the perspective of a focal company. By centering the value proposition on glass recycling, the focal firm and their partners could identify opportunities for collaboration and innovation for glass recycling in different business and industrial contexts.

Following the study by Hsieh et al. [50], many researchers have pursued the direction of studying SBE in the context of the circular economy, where circular BM transformation motivates the need of an ecosystem perspective [32, 34, 51, 52]. They highlight the use of circular BMs to address sustainability challenges and that companies need to work with actors from different industries to close the loop and adopt an ecosystem view to implement circular BMs [12, 31–34]. Within this discussion, Konietzko et al. [33] distinguished between circular BMs and circular ecosystem where the latter considers the BMs of other actors in the BE to be equally important as that of the focal firm. Recently, Trevisan et al. [53] further defined a circular ecosystem as "a system of interdependent and heterogeneous actors that go beyond industrial boundaries and direct the collective efforts toward a circular value proposition, providing opportunities for economic and environmental sustainability".

With the significance of using ecosystems to address sustainability challenges established, researchers have sought to understand how sustainable or circular ecosystems can be developed and encouraged. Konietzko et al. [33] developed a set of principles for circular ecosystem innovation to achieve circularity as a common outcome. The set of principles are categorized into the broad themes of collaboration, experimentation, and platformization. Overall, research in SBEs is still in its infancy and much of what is known are from a limited number of case studies.

2.4 Integrating Sustainable Business Model and Sustainable Business Ecosystem

Although the development in BM and BE research has largely been independent their boundaries intersect. Researchers point out that despite BM being a focal company-centric concept, the concept is embedded in an ecosystem [54] and that companies tap on resources from their BE [55]. Others have also described that BM innovation often lead to the development of new ecosystems [56]. However, such views are still commonly taken from the perspective of the focal company, acknowledging ecosystem partners but failing to provide insights on how other ecosystem members firms align their BMs as part of the BE. Therefore, this intersection has been under-explored with only few authors attempting to build on both streams of research to provide business- and ecosystem-level perspectives [57] (see Glassey-Previdoli et al. [58] for example) to support BM innovation in BEs.

Within BM and BEs for sustainability, there has been considerable research in SBM and a small but recently growing stream in SBE. However, research integrating both aspects to support sustainability is nascent with limited authors starting to discuss SBE as an extension of SBM [33, 50, 52]. Despite so, several researchers have identified the need to support companies wanting to change their BMs or their BE to be more sustainable and have developed methods or framework to do so. These supports can be broadly categorized into a few stages: initialize, design, and experiment (Table 2.1).

Initialize. In the initial stage of identifying the right partners and stakeholders, Bertassini et al. [51] developed a staged approach to guide companies to identify suitable stakeholders and circular innovation opportunities. Important steps include aligning vision and value stakeholders and identifying opportunities for circular value. To understand the transformation to a circular ecosystem, Parida et al. [32] studied large manufacturer ecosystem orchestrators and proposed a two-stage transformation process where the ecosystem orchestrator, or leader, first assesses the sustainability readiness of their ecosystem, followed by using orchestration mechanisms like standardization, nurturing, and negotiation to support ecosystem partners and reduce their risk of adopting the new circular practices. This provided insight into the transformation process but the authors did not develop a usable tool for companies who might want to orchestrate their ecosystem transformation.

Design. Boldrini and Antheaume [59] developed the BM3C2 framework, a SBM tool that can be used at the circular ecosystem level. They integrate the processes of continuously changing BM and alignment of BM with partners. Companies using this tool map first co-identify their sustainable value proposition. They then independently

Table 2.1 Comparison of methods and frameworks integrating SBM and SBE

Stage	Objective	User(s)	Integration of SBM and SBE	Reference
Initialize	Identify and prioritize circular BM opportunities	Focal company	Consider values to different ecosystem stakeholders during the process of identifying circular BM opportunities	[51]
Design	Alignment of value flow between partners	Collaborating companies use the tool together	Companies co-identify SBE value proposition based on understanding of value flow from/to each other's BM	[59]
	Map ecosystem stakeholders required to fulfill sustainable BM	Focal company or ecosystem orchestrator	Design BM with the consideration of ecosystem stakeholders	[58]
Experiment	Assess progress of experimentation of sustainable BE collaboration	Ecosystem orchestrator or focal firm	Track the progress of SBE stakeholders (who have specific SBM)	[60]

and collectively define their resources and competences and map resource flow. This framework transparently allows participating companies to share knowledge and information, enabling them to align their activities and resources.

Glassey-Previdoli et al. [58] developed the Bifocals method to bridge BE and BM design and enable firms to "build and test new BM features to restructure the firm, in response to its ecosystem". All potential actors in the BE are mapped and different BMs are conceptualized to fulfill the value proposition, linking relevant ecosystem actors and the value exchanged between them. The use of this tool allows individual companies to design different BMs considering their BE actors and BM design risks.

Experiment. In the experiment stage, Hubeau et al. [60] developed a sustainability experiment system approach to track and assess the progress of implementing sustainability experiments with multiple stakeholders. By evaluating lists of attributes of the multi-stakeholder experiment during inter-organizational setup, process of the experiments, outcome of the experiments, and performance of the experiments, it encourages consistent monitoring of the experiments and reflection by the actors. Through the authors' study, factors impacting success and failure of the experiments were identified and companies going through the approach can design their experiment process to improve potential for success.

Across the tools, there are themes of working closely with identified ecosystem partners to align goals and agree on value exchange. The processes and tools by Parida et al. [32], Boldrini and Antheaume [59], and Hubeau et al. [60] also consider the iterative alignment process with other actors in the BE. Among these supports, only Hubeau et al. [60], Boldrini and Antheaume [59], and Glassey-Previdoli et al. [58] integrated the perspectives of other actors in the ecosystem while other supports are still focal company-centric and do not consider the external influences of other BE members and their respective BMs. The tools are also limited in focusing on existing stakeholders, not exploring opportunities and innovation outside the industry. Lastly, these tools and frameworks tend to focus on the birth phase of BE lifecycle [17] with limited use in the expansion stage. This could be due to the criticality of the early stage of a circular ecosystem or could also be due to a lack of examples in more mature lifecycle stages available to researchers. Therefore, there is research opportunity to develop understanding and support for companies as they change their BM within their BE to become more sustainable.

2.5 Conclusion

For corporations to develop toward sustainability, transformative change via SBM innovation and working with stakeholders at the ecosystem level is required. In this article, an overview of research in sustainable BM and BE was presented. It was found that despite suggestions of the relevance of BM and BE, research studying how BMs and BE influence each other is lacking, with few describing SBMs together with the BE aspect. Tools supporting practitioners in this process were reviewed but is acknowledged to be limited. Future research can focus on integrating perspectives of multiple key actors in the ecosystem ideation phase and expand the view of the ecosystem to explore cross-industry opportunities. Ecosystem expansion phase or implementation after experimentation with different partners can also be studied.

This study has provided insight on the intersection between sustainable BMs and BEs and identified opportunities to further the development of support for companies to consider how their BMs and their BE change. This can support future development for researchers and practitioners in this research area. A limitation is that the list of tools for BM and BE development is focused on environmental sustainability, lacking the social aspect of sustainability. This could also be an avenue for further research.

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Chapter 3
Sustainability Assessment in Product Design—Perspectives from Finnish Manufacturing Companies

Jyri Hanski, Teuvo Uusitalo, Tuija Rantala, and Jukka Hemilä

Abstract Sustainability has a major impact on manufacturing companies. However, the perspectives of the multifaceted concept of sustainability and sustainability actions vary. Product development has a crucial impact on the sustainability performance of manufacturing companies and entire manufacturing value chains. However, there is uncertainty on how to support the development of sustainable products. The paper addresses two research questions: How sustainability impacts product design in Finnish manufacturing companies and what methods are used in manufacturing companies to assess sustainability in product design? This paper employs qualitative research design and a case-based research strategy. Data is collected from interviews and company workshops with Finnish manufacturing companies. Product design faces many even contradictory sustainability requirements. Identifying the most significant sustainability topics for a specific product design phase and providing suitable methods to support designers pose significant challenges. Of the sustainability assessment methods utilized by companies, only life cycle assessment is directly applicable for supporting product design. There is a need for more comprehensive coverage of social, circularity and criticality aspects, and life cycle thinking in sustainability assessment. In conclusion, this paper presents an initial framework for positioning manufacturing companies based on the scope and importance of sustainability assessment in product design.

3.1 Introduction

The global community is moving in the direction of sustainability, aided by initiatives such as the United Nations' Sustainable Development Goals (SDGs), and the European Union's ambitious sustainability targets, such as achieving climate neutrality by 2050 and the Fit for 55 plan. Manufacturing activities are known to have a significant

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impact on sustainability, so manufacturers are stepping up to implement sustainability programs and report on their progress [1, 2].

Manufacturing activities have an impact that extends beyond production processes, from material extraction to end-of-life activities, and it is estimated that the manufacturing and construction sectors account for one-fifth of global greenhouse gas emissions [3]. As a result, sustainable manufacturing is critical for achieving sustainability goals such as low environmental emissions, efficient resource utilization, and low costs [4].

Sustainable manufacturing considers the three pillars of sustainability: environmental, social, and economic and emphasizes sustainability over the entire product life cycle, manufacturing value chains, and global impacts [5]. The wide scope of sustainable manufacturing is crucial as manufacturing companies must shift their focus from direct emissions and energy use (Scope 1 and 2) to include indirect emissions (Scope 3) [6]. Given the pressing need for sustainability, sustainable manufacturing is a critical and effective approach to achieving sustainability goals. Therefore, it is imperative for manufacturing companies to embrace technologies and practices that reduce their environmental footprint and contribute to a sustainable future.

The circular economy concept is gaining traction as a promising approach to sustainability. Product design plays an important role in this transition. To ensure that sustainable principles are integrated into the design process, sustainability assessment in product design is required. The 9R framework promotes sustainable practices in product design by emphasizing reducing, reusing, recycling, refurbishing, repairing, redesigning, remanufacturing, recovering, and rethinking [7]. Other factors that should be considered include ecodesign, sustainable materials, and life cycle assessment. As a result, companies must prioritize product design in order to achieve sustainability goals and embrace the circular economy concept.

Business models that prioritize longevity of product life cycles, the environment and society are becoming increasingly important. However, determining the long-term viability of such models frequently lacks robust methodologies or takes a narrow view of the larger system. To address this, early in the innovation process, systems thinking can be used to assess the sustainability of business model innovations [8].

While there are several reviews of the literature on product design and sustainability, such as lean and environmental sustainability [9] and the concept of sustainable manufacturing [10], there is a significant gap in research on how manufacturing companies approach sustainability in product development. Existing literature lacks a comprehensive and well-established set of sustainability indicators for manufacturing companies [11, 12], and the use of sustainability assessment methods in manufacturing is poorly documented [1]. As a result, manufacturing companies require assistance in selecting a sustainability assessment framework that is appropriate for their needs and operating environment [13].

In light of these gaps, the purpose of this paper is to identify Finnish manufacturing companies' perspectives on the most critical aspects of sustainability for product design. The research questions are as follows: *How does sustainability impact product design in Finnish manufacturing companies? What methods do these companies use to assess sustainability in product design?*

This paper focuses on Finnish manufacturing companies that participate in the research project DataAsset. These companies have shown interest in developing the sustainability of their products and product development practices. The findings will be used to build a comprehensive sustainability framework tailored to the specific needs of manufacturing companies. This work will contribute to advancing sustainability practices in the manufacturing industry by addressing these critical issues.

3.2 Sustainability in Product Design in Manufacturing Companies

Generally, sustainability can be defined as meeting the present needs without compromising the needs of future generations [14]. Stakeholder perspective is crucial in promoting sustainability [1]. Sustainability considerations of manufacturing focus on decisions regarding the triple bottom line: meeting social demands, environmental preservation, and business profitability [2]. To produce sustainable products, the triple bottom line should be implemented throughout the product life cycle [3].

3.2.1 Sustainable Product Design

Customers are increasingly aware of sustainability, and this results in increased pressure on companies to implement sustainability to product design [4]. For product design, social indicators are not typically used. However, to operationalize strategic sustainability objectives, product development methods and tools used by designers should incorporate the triple bottom line simultaneously [5, 11]. Table 3.1 introduces some of the main sustainability aspects that product design should cover.

Several design for X approaches that aim to enhance the sustainability of products including design for sustainability and design for the environment [1]. Ecodesign aims to find a balance between environmental and economic aspects in product development [15]. Design for X (Design for Excellence) is a systematic approach to achieve an objective that is targeted. X represents the objective or product or system characteristics and may represent assembly, manufacture, maintainability, modularity, life cycle, recycling, environment, and waste minimization [16].

3.2.2 Sustainability Assessment in Product Design

Recently, sustainability assessment has become the focus of performance assessment in manufacturing companies. Focus of sustainability assessment has shifted from

Table 3.1 Sustainable design aspects in manufacturing (Based on [1, 5, 6, 10])

Environmental	Economic	Social
9R	Revenue	User relationship
Resource utilization	Sales	Community relationship
Material selection	Product quality	Supplier relationship
Transport and logistics	Operational costs	Employee health and safety
Durability and longevity	Overall Equipment	Compliance with legislation
Structural and functional considerations	Efficiency	Customer satisfaction
Process selection		Gender equity
Modularity		
Packaging		
Greenhouse gas emissions Waste Energy Water consumption User behavior Resource depletion Toxicity and hazardous production Eco-business Government regulations, laws and guidelines Compliance with environmental regulation		

process to enterprise level and to holistic point of view, multiple parameters, and global sustainability and circularity [11]. Assessing the sustainability state helps manufacturing companies to identify where they are in implementing sustainability [12]. Additionally, sustainability assessment plays a crucial role in manufacturing companies by helping companies to identify and address the environmental, social, and economic impacts of their value chain.

Sustainability assessment can be used to measure sustainability performance of products, services, projects, or organizations by evaluating how well the selected sustainability requirements are fulfilled [5]. The purpose of sustainability assessment is to contribute to a better understanding of sustainability, integrate sustainability into decision-making by assessing impacts and fostering sustainability objectives [13].

There are various sustainability assessment methods and indicators available [5, 10, 17]. However, in practice, sustainability assessment in the manufacturing industry is focused on sustainability of a specific organization instead of absolute (environmental) sustainability improvements [11]. Environmental and economic perspectives are adequately considered in comparison with social perspective that is limited to working environment of employees (safety and employee health) [11]. Table 3.2 introduces typical sustainability assessment methods and guidelines to support sustainable product design in manufacturing.

Table 3.2 Sustainability assessment methods and guidelines supporting product design in manufacturing. Based on [1, 6, 10–12]

Sustainability assessment methods and guidelines
• Ecodesign and design for X [1] • Life cycle sustainability assessment (LCSA) and its modules life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (SLCA) [1, 11, 12] • Carbon footprint and handprint assessment [11] • Reporting frameworks (e.g., GRI) [11] • Standards (e.g., ISO EMS, ISO 26000, OECD) [11] • Ratings and indices (e.g., Ecovadis, LEED green building rating) [11, 12] • Sustainability indicators and checklists [1, 6, 10] • Sustainable value stream mapping (SVSM) [12] • Sustainable operations maturity model (SOMM) [12] • Extent of implementation of sustainable manufacturing practices (SMPs) [12] • Circularity assessment [11] • Criticality assessment [11]

3.3 Research Design

This paper follows qualitative research design to achieve a holistic perspective of the research topic. Qualitative approach enables exploration of alternative research strategies and in-depth analysis of a small number of cases. Case study research is selected as research strategy to collect rich information from small group of manufacturing industry companies. It is suitable for situations that include complex and multiple variables and processes [18]. The selected companies operate in the business-to-business markets (B2B). B2B companies, which have considerable carbon and material footprints, are increasingly facing stakeholder demands to verify their sustainability.

Main data sources in this paper are semi-structured interviews and company workshops. Interview data consisted of 12 semi-structured interviews in 5 different companies operating in the heavy machinery and manufacturing equipment production industries (Table 3.3). The interviewees represented different functions and positions in the company including R&D, production, marketing, and executives to get the comprehensive view of the situation in the case companies. The interviews were recorded and transcribed, and notes were taken. The duration of interviews was 1–1.5 h.

Workshops were organized in 2022 and 2023 (Table 3.4). They focused on gathering more in-depth information on the following topics: WS 1 sustainability in product development (online), WS 2 sustainability assessment (online), WS 3 circular economy activities (online), and WS 4 sustainability in the products and services of the case companies (face to face).

Inductive approach was utilized in analyzing the interviews and workshops data. In the inductive approach, data is collected and explored to identify the themes or issues to follow up and focus on [18]. In this approach, researchers analyze the data as it is collected and develop a conceptual framework to guide the subsequent work

Table 3.3 Interviews data

Company	Main products and services	No of interviewees	Interview date
A	Forestry machinery	2	September 2021
B	Machine equipment	2	September 2021
C	Packaging machinery	3	October 2021
D	Glass heat treatment machinery	4	October 2021
E	Sheet metal processing machinery	1	November 2021

Table 3.4 Workshops data

Company	Main products and services	WS 1	WS 2	WS 3	WS 4
A	Forestry machinery	2	2	0	2
B	Machine equipment	2	2	1	1
C	Packaging machinery	0	0	0	1
D	Glass heat treatment machinery	1	3	2	1
E	Sheet metal processing machinery	2	2	2	2
	Total	7	9	5	7

[19]. The company data was analyzed to provide some perspectives present in the Finnish manufacturing companies on the selected topics.

3.4 Results

3.4.1 How Sustainability Affects Product Design?

Sustainability requirements for product design by the case companies are divided into environmental, social, and economic perspective. Identified environmental requirements focus on reduced energy, CO_2 consumption, and material usage and requirements from regulation and legislation. Social requirements include safety, training, ergonomics, stakeholder perspective, and fair sharing of value in value chains. Economic requirements include cost-effectiveness, production efficiency, long-term returns for shareholders, and extended machine lifetime with maximal asset value.

Product life cycle is considered limitedly, even though it has a major impact on product design. In the future, importance of life cycle perspective is thought to increase with increased circularity opportunities. Companies aim to manufacture high quality, energy-efficient products with long lifetimes and reduced use of materials. Life cycle is mainly considered when determining greenhouse gas emissions over value chain or with products that have long lifetimes and product design needs to consider service, repair, and upgrades. Table 3.5 introduces key questions for the product design over product life cycle from OEM's perspective.

Table 3.5 Key questions for product design over life cycle identified by the case companies

Product design	Production	Operation and service	End of life
Is machine usage and work site data available to understand customer needs?	What is the energy consumption of the machine?	By how much the machine lifetime can be extended?	How much of the machine can be recycled (%)?
How much recycled material has been used in the production of the machine? (eco-friendly materials)	What is material saving when parts are manufactured with the machine?	What is the sustainability vision/ sustainability targets for the next 5–10 years?	What materials are used for the machine?
What do we need to consider in machine design to help our customers get sustainability certifications on EU level?	How much CO_2 is used in the manufacturing process?	What kind of technological trends should be considered?	What is the component and software content of end-of-life products?
What kind of technology should be used?	Is there a need for collecting more components to own storage in case of component shortage?	How can we automate the process of detecting anomalies in machine operations and turn data into corrective actions for our customers?	Can we support customers to recycle raw materials and make less waste?
	Is it possible to use second choice components instead of first choice?	What are the customer use cases?	
		Can we evaluate machine and operator performance against benchmark?	
		Can we identify new ways to use the machine to reduce energy and waste?	

3.4.2 How is Sustainability Assessed?

In general, there were two distinct perspectives for sustainability assessment. First, sustainability assessment focuses mostly on economic perspective due to customer focus on economic benefits. Other impacts are important in case demanded by customers or financiers. Second, all TBL aspects are important, also life cycle approach, circularity aspects, and increasingly biodiversity.

Table 3.6 introduces the findings related to the sustainability assessment in the case companies. Most findings are related to product design but also cover wider topics such as sustainability reporting and stakeholder perspective.

There are a variety of reasons for adopting sustainability assessment from mandatory reporting and EU policies to stakeholder and customer requirements to supporting product development. Methods and applications for sustainability assessment focus on sustainability reporting and rating services, but also life cycle assessment (LCA) over value chain of companies and screening methods are mentioned. Target groups are defined for specific sustainability information and sustainability assessment is driven by marketing, sales, and requirements in standards. Challenges for sustainability assessment include selecting assessment framework and scope, data availability and quality, complexity of products, assessment of social sustainability, and commitment of employees to sustainability assessment and goals.

Considering the multitude of requirements faced by product designers, a simplified framework for positioning the sustainability assessment in product design would be helpful. Figure 3.1 introduces, through a simple matrix, how manufacturing companies could position themselves based on the importance and scope of sustainability assessment in product design. The importance refers to the strategic commitment

Table 3.6 Sustainability assessment in the cases companies

Why?	Methods and applications	Key challenges
Mandatory sustainability reporting	Annual sustainability report with key performance indicators	Selecting sustainability assessment framework
Customer requirement—certificates and sustainability information	Sustainability rating services	Suitable level of assessment (cradle to cradle, cradle to gate, etc.) may vary according to stakeholder
Shareholder and financier requirements	Verifiable science-based targets and public records	Time-consuming project with uncertainties
Product development	LCA and Scope 3 emission calculations	Identify and obtain relevant data Deficient data
Promoting awareness of cost structure and life cycle costs	Exploring applicability of screening methods	Data accuracy and knowledge develops over time Complex products with long life cycles
Showing impact of business on society		Social sustainability
EU Green Deal and other policies, e.g., ecodesign directive and product passport		Sustainability needs to be in the enterprise strategy or results might be neglected Project management: How to commit people to goals and targets?

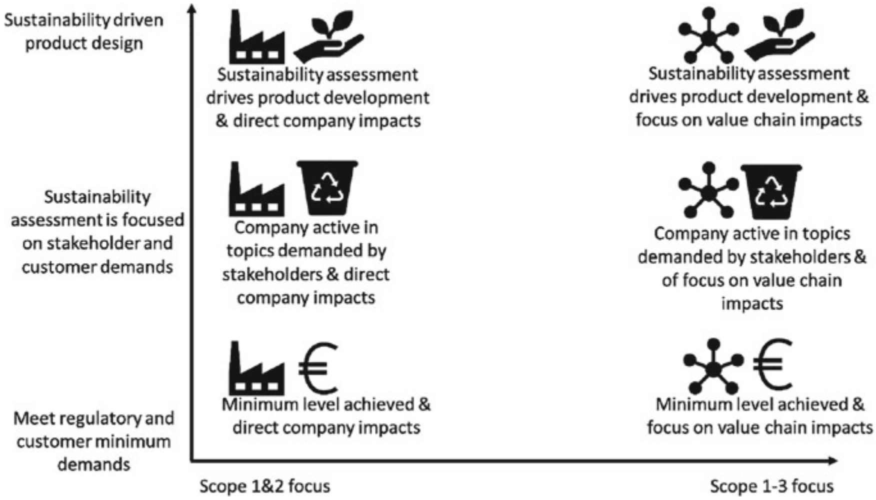

Fig. 3.1 Positioning the sustainability assessment in product design

of companies to improve the sustainability of their products and product design, starting from (1) meeting the minimum requirements, (2) to focusing on stakeholder demands, and finally, (3) to the strategic choice of optimizing sustainability in products and product design. Scope refers to (1) the Scope 1 and Scope 2 emissions, which include emissions from direct sources controlled by the organization and indirect emissions from the energy use, and (2) Scope 3 emissions, which also focus on the indirect emissions from organization's value chain.

3.5 Discussion and Conclusions

The paper aims to answer two main research questions: How sustainability impacts product design in Finnish manufacturing companies and what methods are used in manufacturing companies to assess sustainability in product design? Even though companies are currently at different levels of adopting sustainability principles, emerging customer and stakeholder demands force all companies to consider the importance of sustainability in their business.

Product design faces many contradictory sustainability requirements, and it is essential to provide understanding of the factors affecting product sustainability. Considering the environmental sustainability aspects in Table 3.1, many of them are covered in the companies. The challenge is to identify the most important sustainability topics for the specific product design phases and how to provide adequate methods to support the designers. Economic perspective is extended to consider the whole life cycle and it is questionable if increased sustainability can be translated to decreased costs or increased income from customers. Social perspective is on the rise as companies recognize the drastic brand impacts and fines of not focusing on them properly.

As shown in Table 3.5, design phase is focused on the availability of data from customers' processes, recycled and eco-friendly material content in products, supporting customer's sustainability targets and sustainable technology selection. However, production, operation and service, and end of life phases set further requirements to design phase: lower energy consumption and emissions, reduced material usage, component substitution in case of shortage, product life extension, anomality detection in machine operations, improvements based on product and operator performance evaluation, recyclability, product material and software content, and waste minimization.

Table 3.2 presents a list of methods for supporting sustainable product design. More research is needed on how the methods support specific activities in product design. For instance, LCA and circularity assessment methods may provide different results on, for instance, if recycled materials should be used in manufacturing of products or if the product, or part of it, should be recycled and by which method.

Of sustainability assessment methods utilized by companies, only LCA could be directly applicable for supporting product design (Table 3.6). Sustainability reports and rating services may also provide supporting data for setting targets for product design. Hopefully, with the wider market penetration of sustainability rating services and concrete and comparable sustainability performance, companies increasingly shift their focus to sustainability assessment in product development. However, application of methods such as those listed in Table 3.2 could be highly beneficial for more holistic understanding of long-term sustainability impacts in product design. For environmental impacts, some companies are still in the process of identification of the major CO_2 emission sources and the prioritization of the identified actions points. We suggest more comprehensive coverage of social, circularity and criticality aspects and life cycle thinking in sustainability assessment to support product design.

Sustainability goals in product design should be grounded in sustainability strategy and objectives. More research is needed to determine who sets requirements for sustainability in product design: top management, marketing department, sustainability reporting, or product development itself? To ensure the realization of the objectives, more focus is needed for tailoring the data management process including collection, analysis, utilization, and reporting to support the sustainability assessment in product design. Other research topics include magnitude of sustainability knowledge transfer inside companies and potential silos in reporting and product development.

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Chapter 4
Measuring Sustainability in Wood Fibre-Based Production Chain

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Abstract In the previous literature, measuring sustainability in the production chain has not been extensively studied. Therefore, in this paper, we examine how sustainability is measured in the wood fibre-based production chain. We explore the theme by presenting the findings from 2 workshops and 16 recent interviews with executives of 10 companies involved in the production chain. The interviewees recognised the value of sustainability from the perspectives of saving the planet, the company/employee images, competitive advantage and cost savings. In this study, we highlight the economic sustainability key performance indicators (KPIs) as challenging and requiring further studies and methods. We also emphasise the fact that sustainability data would not only comply with reporting requirements but would also increase and improve the sustainability performance of industrial operations and processes. Managerial and theoretical implications consist of clarifying and synthesising scattered viewpoints about measuring sustainability since practical sustainability-related indicators and KPIs are presented in this paper.

4.1 Introduction

The main objective of sustainability is to respond to current needs without compromising ecological systems, social justice and the well-being of future generations [1, 2]. Industrial companies must take into account not only economic but also environmental and social objectives in their businesses. Thus, these sustainability objectives occur at all stages of the life cycle of each company's value network [3].

Sustainable manufacturing focuses on the efficient and effective use of natural resources by creating products and solutions that can meet sustainability objectives while further improving people's quality of life [4, 5]. In manufacturing practice,

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sustainability means paying attention to on minimising the environmental impacts of production, adhering to social norms, promoting well-being and generating business benefits [6, 7].

The use of information and information technology, hence digitalisation, may change the ways that value is created and enable societies to be more resource efficient and sustainably impactful (see, e.g., [8–10]). Tallon et al. [10] rightly reminded readers that what information technology will do in the future is not same as what it did in the past. Indeed, the development of many circular economy solutions is supported or even enabled by data collection through digital solutions and platforms, data analysis and the utilisation of these results in decision-making. Measuring sustainability, sustainability-related indicators and key performance indicators (KPIs) are not widely studied in the manufacturing industry. There is a need for an in-depth understanding, expanded frameworks and advanced models to learn how to measure sustainability with a broader scope, not only from the climate change or circular economy perspective, which are often the areas of focus of sustainability targets in industrial actions.

In this study, our aim is to enhance the understanding of the main sustainability-related indicators and KPIs in the wood fibre-based production chain. Thus, we pose two research questions:

1. How do manufacturing companies value sustainability in the production chain?
2. How do manufacturing companies measure sustainability in the production chain, and what kinds of challenges are encountered in the process of measuring sustainability?

4.2 Background Review—Reasons for Measuring Sustainability

The United Nations Environment Programme [11] defines five key drivers of the nature crisis. These drivers are: (1) changes in land and sea uses, (2) climate change, (3) pollution, (4) direct exploitation of natural resources and (5) invasive species. All these drivers have direct impacts on human welfare, as well as on companies and their businesses. Hence, the fear of biodiversity and natural capital loss play an increasingly central role in companies' sustainability work, in addition to climate change-related targets.

Another dimension of sustainability development involves responsibility and human rights. Taking care of human rights is vital for social responsibility. Diversity, inclusiveness and intersectionality are not only human rights issues, but they can also be perceived as directly connected to a company's ability to operate and achieve success. The new directive on corporate responsibility legislation proposed by the European Commission [12] is intended to make companies' sustainability reports more precise. Another forthcoming directive on corporate sustainability due diligence [13] aims to foster sustainable and responsible corporate behaviour, as well as anchor human rights and environmental considerations in companies' operations and corporate governance.

However, when sustainability is discussed, the economic aspect is often overlooked. From the sustainability standpoint, positive economic impacts arise, for example, from savings and risk management. Sustainable operations reduce the usage of energy, water and other raw materials. Risk management—which can mean the prevention of disturbances, accidents or various complaints related to the company's operations, financial risk management and so on—in turn creates better operating conditions and continuity for the company.

The concept of double materiality is included in the CSDDD, and it brings in the integration of financial targets and societal impacts. Companies are asked to report not only how sustainability issues might create financial risks for them (financial materiality) but also their own impacts on people and the environment (impact materiality) [14].

The main challenge in measuring sustainability still lies in selecting the right set of indicators [15, 16]. In practice, this is done in the materiality analysis of the industrial process, where the whole process is covered, and the most impactful and meaningful indicators are selected. Based on their study, [16] suggest that sustainability KPIs are related to financial indicators, internal processes, learning and growth, as well as customer, environmental and social perspectives.

Financial indicators refer mainly to investment returns, while internal processes focus on recycling or certification and so on [17]. In learning and growth, labour efficiency and technology use are considered. Customer aspects refer to markets and customer satisfaction, among others. Environmental KPIs include energy, water, materials and environmental impacts. Finally, social indicators highlight community relationships, safety and employee satisfaction [16].

4.2.1 Sustainability Data and Related Challenges

In this study, we define sustainability data "as any data that enables sustainable innovations, increased sustainability performance or indication of sustainability in companies" [3, p. 2]. Sustainability data comprise several data sources, such as sustainability reporting-related data, process data and energy-use data. For example, monitoring energy use throughout the production chain could provide sustainability data for direct actions, enhancing sustainability, making the production chain more transparent and indicating sustainability levels in annual reports.

However, there are many challenges concerning ratings and sustainability indicators, especially those related to data. Comparable figures can be difficult to obtain. Data are collected digitally from reports and websites. Classifications do not consider national differences, for example, in legislation. Data are not reliable [3, 18]. Reference [18] examined the challenges faced by the manufacturing industry and the overall sustainability situation, concluding that the Sustainable Development Goals

(SDGs) have not been fully realised and that there is a need for greater integration of sustainability and decision-making. The lack of suitable metrics and demand for sustainability, as well as limited understanding and awareness of the impacts of non-compliance, are key obstacles to the pursuit of sustainability-related activities [18].

For businesses, providing data and information for various evaluations and listings can be a tedious and time-consuming process. The transparency of the processes employed by the companies under the sustainability rating also leaves something to be desired. Due to both future regulations and different stakeholders' expectations and requirements for reporting, companies will also need to consider the format and interface of their reporting.

One way to address sustainable production is through the circular economy, which is an economic model that aims to contribute to achieving the SDGs through resource-use measures and waste reduction. The role of data and information is essential in the circular economy, as they monitor resources, enabling actions to be allocated correctly, efficiently and quickly to achieve a profitable and sustainable circular economy.

4.2.2 Sustainability Reporting

A wood fibre-based manufacturing process uses wood fibres as the primary raw materials to produce a variety of products, such as paper, cardboard, textiles and biofuels. The process typically involves harvesting trees, chipping the wood into small pieces and using chemical and mechanical processes to break down the wood fibres into pulp that can be processed and turned into various end products. In this paper, the *wood fibre-based production chain refers to the production of goods based on wood fibre raw materials, from forest to consumer products.* The production chain's key operations include harvesting, pulping, paper/board making and converting, involving all actors related to the production chain.

The manufacturing industry is in the process of transition from Industry 4.0 to 5.0 [19]. While Industry 4.0 addresses the technology involved, Industry 5.0 seeks to bring human, environmental and social aspects into focus. Reference [20] argue that the current exploration of Industry 5.0 is still in its infancy and that relevant research findings are relatively scarce and hardly systematic. There is thus a gap to be filled by research. Industry 5.0 addresses the environmental and social dimensions of sustainability data and data sharing.

Sustainability reporting focuses on human, environmental and social aspects of sustainability. The reporting is currently undergoing a transformation, and its development is accelerated by changes in the regulatory field, making the reporting more formal than previously done. The most significant changes will likely be brought by the new CSRD [12], which entered into force in early 2023, and the draft [13]. The standards governing the social and environmental data that businesses are required to provide have been modernised and strengthened by the new directive. There will be new requirements for data quality, reliability and transparency, and reporting obligations will expand to cover a significantly larger number of companies. The digital potential of information management has also been highlighted in the new directive.

In the future, sustainability reporting will be increasingly subjected to verification. The certifier's task is to review the materiality and reliability of the reported data. A new dimension added to sustainability data reporting is provided by the digital reporting model, which aims to increase the usability of the data.

Sustainability ratings are part of the investor's tools for assessing the ESG performance of funds and investment targets [21, 22]. ESG stands for "environmental, social and governance" and refers to issues within these three dimensions. These three dimensions also denote key areas of corporate responsibility. For its part, the EU Taxonomy Regulation defines the sustainability criteria for investors. Taxonomy Decree defines the classification and criteria that can be used to identify funding and investment targets that are considered sustainable in the future. Sustainability ratings help investors assess how well companies manage sustainability-related issues and risks, investors then take advantage of the opportunities arising from such challenges. The media is also interested in the information provided by current ratings.

4.3 Methodology

We utilise a qualitative case study as our research approach. The case-study technique was chosen due to its suitability for situations involving complex and multiple variables and processes [23]. The qualitative data were collected from interviews with 16 executives from 10 companies, covering their management of sustainability, research and digital solutions between September and November 2022 (Table 4.1). The businesses under study comprised operators and actors in the renewable forest and chemical industries, as well as companies serving the complete chain. The wood fibre industry was selected because sustainability and biodiversity are very significant and timely aspects for the case companies. Renewable materials, loss of forests and carbon sinks feed the debate in the industry. The wood fibre industry is pressured to use renewable raw materials and implement sustainable processes and work operations and is thus a very interesting sector.

The interviews conducted by one or two interviewers lasted 1 to 1.5 h each. Because the study is partially exploratory in nature and the meanings of concepts needed to be negotiated with the interviewees, semi-structured theme interviews were selected as the primary sources of empirical materials. The interviews went beyond sustainability and the role of data to thoroughly understand the case companies' businesses and their viewpoints on sustainability. The interviews included questions such as the following: What is the value of the Sustainability Development Goals? Why do you want to achieve those goals? What measures do you want to take to achieve those goals? Who defines sustainability KPIs in your company? How do different actors in the value chain see sustainability and sustainability KPIs? Additionally, several questions were related to value-chain perspectives, monitoring, measuring,

Table 4.1 Interviewed company executives, the companies' main products and services, number of interviewees and interview dates

Company	Main products and services	Number of interviewees	Interview date
A	Machinery, lifting business	2	September and October 2022
B	Machinery, paper making and automation systems	1	September 2022
C	Machinery, valves	2	September 2022
D	Retailer	1	October 2022
E	Software	1	October 2022
F	Chemical industry	2	September 2022
G	Forest industry	2	September 2022
H	Forest industry, bio-based materials	1	September 2022
I	Forest industry, harvesting machinery	2	November 2022
J	Digital consulting	2	November 2022

tracing and optimising sustainability-related actions. The same questionnaire was used in all interviews.

The findings have been refined through several discussions with the researchers, and a workshop attended by the company and researcher representatives was held on 24 November 2022 to analyse the interview findings. Another workshop for the purpose of collecting the main KPIs of the production chain was conducted on 1 February 2023, with 14 participants from 6 companies and 3 research organisations. Qualitative materials were gathered from discussions at the VTT Technical Research Centre of Finland's responsibility seminar entitled "Strong Stronger Responsible", which was held in Tampere on 19 October 2022. The seminar included a panel discussion with several company representatives about sustainability and data utilisation. Interview tapes and notes, as well as workshop and seminar conversation notes, were included in the qualitative data.

4.4 Results

4.4.1 Value of Sustainability for the Company

In the interviews, the company executives were asked what the goal of sustainable development was and what value sustainable development had for them. The values identified in the interviews are shown in Fig. 4.1. The interviewees presented a wide range of perspectives. In the big picture, the emphasis was on the companies' contributions to saving the entire planet—which were not at odds with the business.

Fig. 4.1 Value of sustainability for the case companies

> We are dependent on the operating conditions of the future, and thus, we must take care of the operating environment so that there are raw materials in the future and so that the business can exist in the future. (Company D, executive #1)

Support for biodiversity was highlighted in the interviews, as was social responsibility in the supply chain. One company executive stressed that when forming sustainability goals and setting requirements, these should be discussed with suppliers. Thus, demanding unpredictable things from suppliers and causing troubles for their businesses could be avoided. Additionally, some companies wanted to lead the way in sustainability by creating sustainable solutions on their own initiative. In this case, they were moving proactively and not just starting when they must.

Today, investors and consumers also demand responsible behaviour from companies. In terms of company and employer image, large international organisations desire to be interesting investment targets. Customers' (especially consumers') awareness of and demand for sustainability are also increasing. Thus, the market steers operations in the direction of sustainability.

The availability of labour has become more difficult in many sectors, leading to competition for skilled labour. The interviewees also highlighted the impact of the corporate commitment to sustainability on the employer's image, both from the perspective of the availability of a new workforce and in the eyes of the company's own personnel, so that the company's operations align with the personnel's own values.

> Younger people are used to sorting and recycling, and, of course, you can't do anything worse than how young people work at home. The attitudes of the personnel must be taken into account in the company's operations. (Company C, executive #1)

From a business standpoint, sustainable solutions can provide a competitive advantage to the company and added value to customers, for example, in the form of more energy-efficient solutions or new sustainability-related services. In turn, cost savings are achieved by improving operational efficiency and in material-intensive products/sectors, by eliminating waste.

4.4.2 Sustainability-Related KPIs in the Production Chain

Based on the interview findings, sustainability metrics are usually defined at the corporate level, where a sustainability team first prepares the metrics, which are then approved by the management team or the board of directors. Factors, such as ISO 14001 standards, the energy-efficient agreement Motiva, the Corporate Responsibility Act, the science-based targets, EU CSRD and the legislation of the food industry had impacts on defining and choosing the suitable metrics, according to the interviewees. After choosing the metrics, some of the identified key challenges were how to transparently collect the digital life cycle data of a product, store the data obtained from the indicators and clarify the data after a long period of time.

According to the interviewees, the identified environmental indicators were mostly traditional metrics related to energy consumption, heating, water and gas usage, recycling and transportation distances. The interviewees also mentioned several ways of calculating emissions such as the Life Cycle Assessment (LCA), carbon footprint, Volatile Organic Compounds (VOC) emissions, SCOPE 1, 2, 3 emissions, and direct and indirect greenhouse gas emissions. In the social dimensions, the indicators were related to work community, occupational safety, well-being, ethics and social responsibility (e.g., employment duration, average age, gender distribution, tax policy, human rights, work conditions, child labour, product quality and safety). Well-being and voluntary turnover were highlighted in the interviews. On the financial side, the listed indicators included operating results, cash exchange, self-sufficiency, strategy, anti-corruption, taxes paid, cost of transport damage, turnover of refurbished parts and other indicators related to net sales. Additionally, product functionality, possibility of replacements, condition monitoring, potential new applications and innovations were associated with the economic dimension.

Subsequently, the indicators and KPIs related to different phases of the production chain and the interview findings were discussed in a workshop. Focusing on a specific phase enabled the participants to identify indicators for each of the three sustainability dimensions, as presented in Figs. 4.2 and 4.3. In the discussions, economic and in some phases, social indicators were not as clearly identified or known, as can be seen in the figures. The reasons could be the lack of understanding of suitable indicators for measuring economic sustainability later in the supply chain or of the impacts of economic and social indicators.

Figure 4.2 presents the indicators and KPIs for the production chain from the suppliers' perspectives. Figure 4.3 presents the identified indicators and KPIs from the customers' perspectives, which include the metrics that fulfil the customer requirements in terms of sustainability. The brand owner, the retailer and consumers are part of the supply chain, but their requirements have a more explicit impact on the metrics, thus creating the need for their own perspectives. The brand owner may also be perceived as encompassing an overarching phase that connects to all other phases of the production chain.

	Raw material supply	Raw material processing	Production & further converting
Environment	Amount of bio-based raw materials Share of recyclable inorganic raw materials Use of recycled parts or materials Land use Share of food from certified forests Thinning intensity and density of remaining trees Positive impact on biodiversity – total positive/negative Share of renewable fuels Carbon emissions Carbon footprint Transportation emissions/distance (CO2/km)	Water usage Efficiency (time, raw material, production, loss) Reduction of energy and water usage Utilisation of production side streams Logistics emissions External impacts from production (chemical and water emissions) Effects on local water bodies	Efficiency (lead time, operational control, energy usage, material, production, waste) Lost material Reduction of waste Recycling degree and level Final disposal of waste Carbon footprint and handprint Traceability Resilience to extreme phenomena Material balance (in/out)
Social	Number of absences Employee safety Occupational safety Inclusion and diversity Human rights Percentage of women in workforce Minimum wage issues included in company targets Finished products meet product safety regulations	Occupational safety Availability of employees Attractiveness and retention Work motivation Meaningfulness of work Social acceptability	Occupational safety Chemical safety Absences from work Human rights
Economic & Governance	Change in turnover of bio-based products Cost of teaching machinery usage Working efficiency (h) Fuel consumption costs	Logistics cost	

Fig. 4.2 Most important indicators and KPIs in the production chain—supplier perspective

	Brand owner	Retailer	Consumers
Environment	Transition to renewables and recyclability Raw material efficiency Biodegradability and recyclability Carbon footprint Net Promoter Score (NPS)	Lost material Amount of waste	Longevity and quality Recovery of used products Recycling degree Transparency
Social	Meaningfulness & significance of work	Awareness	Product safety Transparency
Economic & Governance	Increase of sustainable product income Willingness to pay for sustainable products Share of FSC-certified products		

Fig. 4.3 Most important indicators and KPIs in the production chain—customer perspective

4.5 Discussion and Conclusions

First, identifying sustainability indicators and defining their contents are critical aspects for measuring sustainability. In this context, it is important to identify data that are relevant to operations and optimisation of operations. Second, identifying and collecting critical sustainability data are also essential. It is crucial to understand what sustainability data have been and have not yet been collected, the data quality and reliability, as well as opportunities for real-time collection.

For example, according to our study, no significant economic KPIs were obtained in the sustainability context. This is probably because economic-related KPIs were not as easily identified compared with environmental indicators. This was especially observed at the end of the production and supply chain. Perhaps sustainability aspects do not stimulate a discussion on economic issues but mainly on environmental issues, thus causing a lack of understanding or issues in identifying economic indicators. In contrast, [16] tackle economic aspects as investment returns. Economic indicators can also be observed in other KPIs. For instance, employee satisfaction is a good indicator for measuring and developing both social and economic performance. Furthermore, improvements in the efficiency of processes may generate economic benefits, along with environmental and social advantages.

The key to identifying sustainability indicators and the sustainability data behind them is to analyse materiality. It is used to identify the impacts of sustainability-related activities on an organisation's sense of responsibility, the formation of business and the surrounding society. The analysis could help overcome companies' struggle with data collection, especially with the sustainability data. In practice, the data might have been collected already but are not perceived as sustainability data. There may be also lack in understanding of what data are needed or missing, or there may be challenges with the quality and transparency of the data.

The process of transition from the technology-oriented Industry 4.0 to the human-centric Industry 5.0 reflects the challenges identified in our study. The data on human, environmental and societal aspects have neither been identified nor systematically collected and shared so far. There is a clear need to develop definitions of sustainability KPIs, improve the data collection and create common platforms where the data can be shared, regarding this industrial revolution as well. Our results are in line with [15] findings that every company wants to be able to measure its sustainability performance and that a high number of KPIs are available but without uniformity.

In this paper, we also note that sustainability data would not just comply with reporting requirements but would also increase and improve the sustainability performance of industrial operations and processes. For instance, sustainability ratings could also be used in business development, not just in sustainability reporting. Our findings are consistent with another study's [18] results that sustainability goals are not yet fully realised and there is a need for integrating sustainability into decision-making.

Our paper presents practical findings from interviews and workshops concerning the wood fibre-based production chain. These are valuable for company managers' plans for their sustainability actions in the future. Our explorative study with its limited sample only scratches the surface but opens up several interesting paths to take in the future. Our sample was too small to draw company- or industry-specific conclusions. The company executives mentioned that they had challenges in identifying the most suitable sustainability indicators and were only in the beginning of the sustainability journey from the production chain perspective. Many interesting questions have to be answered in future studies as well. For instance, why do some companies choose certain indicators over others? Is this somehow related to the characteristics of the companies? How useful are the indicators? How can they be improved? Can companies actually gather all the data that they would find useful? Why do all of these matter—do they have relevance for economic development, regional industrial restructuring, addressing power imbalances in supply chains and so on? Questions such as these would be intriguing to answer in future studies and relate to existing literature. More in-depth research is needed to answer previous questions and to develop a holistic sustainability measurement framework and indicators. Thus, more comprehensive investigations of the customer-side KPIs can provide a better understanding as our limited sample only reveals the tip of the iceberg.

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Chapter 5
Digitalization Strategy for Sustainable Transport in the Construction Sector

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Abstract The construction sector is under a strong transformation, partly due to accelerating digitalization and partly due to an increase in sustainability requirements. The drivers of digitalization are increased productivity, efficiency, and quality, whereas the requirements on sustainability performance are related to many external forces impacting the sector, such as stricter regulations on the verifiability of claims concerning total resource efficiency, emissions, and waste management. In particular, this leads to the transport actors within the construction sector who need a strategy to digitalize their sustainability information handling, from data sources on vehicle, fuel, good, endpoints, and routes to total logistics commissions and projects, as well as how to integrate their data and information with other actors in the construction sector. This paper investigates this issue by assessing approaches to this combined challenge and shows how to integrate data exchange standards of the construction sector (the Swedish BEAst and the international PEPPOL) with an ISO standard for controlling the verifiability of quantitative sustainability information. The research shows how such standards-based requirements on data exchange between and from all construction transport actors and stakeholders throughout full product life cycles and total transport chains enable digitalization and data flows in a cost-efficient way and with short lead time. This in turn intends to reduce administrational costs and errors, as well as facilitate follow-up, traceability, verifiability, efficiency, as well as improves the managerial control necessary to reduce societal and environmental risks.

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5.1 Introduction

Both the construction and the transport sector are under strong transformational changes due to increasing sustainability demands. In European Union (EU), this is expressed by several directives both in the sustainability domain [1–3] and in the field of digitalization to increase service levels, safety aspects, product quality, overall efficiency as well as to decrease economic costs and sustainability impacts [4, 5]. For example, Level(s), the European framework for sustainable buildings [6], advocates for the monitoring of sustainability impacts of buildings through various lenses. Environmental performance across the entire life cycle is a crucial aspect, involving the tracking of greenhouse gas emissions throughout the building's life span, ensuring resource efficiency, adopting circular life cycles for materials, and promoting the efficient use of water resources. Furthermore, Level(s) highlights the significance of prioritizing occupants' health and comfort, aiming to create spaces that are not only environmentally friendly but also conducive to the well-being of those utilizing them. Additionally, the framework emphasizes the importance of considering cost, value, and risk, encouraging adaptation and resilience to address the challenges posed by climate change.

The transport and construction sectors are inherently distinct, representing physical buildings and transportation services, respectively. Despite their dissimilarities, an intriguing convergence occurs when transport services are utilized within the construction sector. In this context, they exhibit a notable similarity. Unlike general transportation services that can often adapt to various scenarios and local conditions, their role within the construction sector necessitates a more complex approach. The sustainability performance of transport in construction case depends on detailed decisions at different stages of the life cycle and at all systems levels. The responsibility for these sustainability impacts is distributed across multiple stakeholders in the construction sector (owners, developers and investors; design teams (architects and engineers); construction and demolition companies, construction managers, lead contractors; organizations that occupy buildings, etc.), as well as in transport sector (such as transport user (consigner, consignee); transportation service provider; warehouse provider; Lead Logistics Provider (4PL); transport forwarder; transport operator, including vehicle operator [7]).

This emphasizes that sustainability management of the construction sector's transports includes a wide variety of sustainability parameters to be coordinated between many different stakeholders. Such coordination needs effective and well-structured digitalization, so that each acting stakeholder can be correctly and relevantly informed. For example, a recent study shows that the sustainability-related efficiency of land logistics systems in the EU is very low [8]. The authors conclude that from the policy point of view, a higher level of environmental performance could be achieved by improving the modernization of existing infrastructures through the support of digital technologies. This research addresses which standards are needed to apply for sharing high quality data about relevant sustainability issues so that the right decision maker can be correctly informed and advised at each level of an organization.

Decision makers throughout a construction project have many different contact points, transport occurrences, transport operators, etc. Over a stretched period, it is a challenge to keep track of all data consistently and verifiably through the different communication channels, from requirement setters down to operations, and again back up to reporting and decision making and control, each with relevant data at relevant level of detail. This requires a well-designed operational information system that serves each decision maker and allows for both the lowest level of detailed data, up to highly aggregated data for large-scale construction projects and their role and interactions with their local, regional, and global sustainability impacts. The research addresses that challenge through a standards-based strategic digitalization process for the transport sustainability data of large-scale construction projects.

The process and methodology are designed to link all relevant sustainability-related, categorical, and measurable entities of construction project transports, such as types of vehicles and energy sources to individual loads of building materials, as well as any relevant geo-fencing data.

Due to the need to exchange data between multiple parties within different sectors, at different geographical locations, using different information systems and languages, we have focused on sector and technology independent data formats-based international standards. Initially, this led to Swedish construction sector-based open data format BEAst [9] for data exchange, and the international standard ISO 14033 Environmental management–Quantitative environmental information–Guidelines and examples [10] as framework to ensure high quality and relevant sustainability data to enter into the data exchange format. BEAst is of interest since it focuses on an open data exchange format, which is fully specified and machine-readable, and hence can be communicated effectively and efficiently between different actors in the construction sector in general. Consequently, it also facilitates data exchange between actors in a construction project. ISO 14033 includes two different graphical modeling languages to enable verifiable information. The first (Fig. 5.3) describes how some measurable quantity via measurement and data management becomes meaningful information, or conversely, how to produce measurement data to obtain meaningful information. The second (Fig. 5.4) describes how different levels of already meaningful information are combined into new meaningful information, or conversely, how to find which information needs to be combined to obtain some specific meaningful information.

5.2 Background

5.2.1 Sustainable Development of Transport in the Construction Sector

Transport in the construction sector accounts for a significant part of the climate impact [11]. Thus, it is in need of modern sustainable solutions. One of the key methods that can help to achieve more sustainable development in transport within the construction sector is the *Green Transport Modes*, such as electrification and choice of fuel. There are three major concepts of Electric Road Systems (ERS): (a) conductive overhead lines/catenary technology, (b) conductive rails, and (c) wireless induction technologies that are currently in different stages of demonstration. Conductive overhead lines/catenary technology builds on the same idea as the railway, with roadside support masts to hold contact cables about 5 m above the road [12]. Overhead transmission is the most developed solution today and has no direct impact on the road construction, which leads to easier maintenance of both transmission and road network. However, it requires extra infrastructure, i.e., the support masts that visually impact the landscape [13]. This solution is only suitable for heavy traffic and scheduled traffic but not, for example, for passenger vehicles. Conductive rails are the technology solution that can be installed in the road surface, bolted upon the surface, or at the side of the road [12]. This technology can be used for heavy-duty and distribution trucks as well as for passenger vehicles. The third type, wireless induction, is the most mobile solution since the vehicle and the road create contact via magnetic radiation instead of physical contact. There are many advantages of such technology; for example, regular road maintenance and operations (e.g., snow plowing or preventive anti-icing) will not be affected by or harm the technology itself. However, there are concerns about risks for people around the magnetic radiation [14].

The report written by Kloo and Larsson [14] presents the analysis of today's technologies/fuels (hydrogenated vegetable oil (HVO), hydrogen/ fuel cells and battery) and future goals for heavy goods transport. Nowadays, diesel fuel is used to the greatest extent in goods transport. Since the majority of all diesel vehicles can be fueled with biodiesel, existing vehicles and distribution can be used. Biogas in gaseous form of compressed biogas (CBG) is not fully compatible with the engines in heavier traffic, the efficiency of CBG is lower, and today's engines have to be modified. Biogas can also be used in liquid form (i.e., liquefied biogas, LBG), which is compatible with diesel cars, but this technology requires more expensive and more advanced technology for storage and distribution [14]. Fuel cell-powered vehicles that run on hydrogen are still in the research stage. The research development is progressing rapidly, but it has not taken the same pace as the development of battery operation. At the same time, hydrogen is seen as one of the fuels of the future. With the transition to an electrified vehicle fleet, batteries are crucial in the deployment of zero-emission mobility and intermittent renewable energy storage, and in the EU's transition to a climate-neutral economy [15, 16]. The technology for battery vehicles is the most environmentally smart choice as the vehicles are emission-free during the operating phase and create less noise compared to fossil-powered ones [14]. However, as the battery capacity and charging options are not sufficiently developed, it makes longer transports more difficult [13]. Therefore, the possibility of hybrid solutions to create a cleaner urban environment via electricity and the possibility of using hydrogen, HVO or other hybrid solutions for longer distances sound more relevant at the current stage (ibid).

Another key method that can help to achieve more sustainable development in transport within the construction sector is the *efficient logistics and operations* such as route optimization, consolidation, and collaboration, as well as efficient vehicle use. For example, Bergman [17] claims that with good construction logistics, the number of transports to and from a construction site can be reduced by 60–80% when building houses. Fredriksson et al. [11] also describe that by coordinating transport between different construction sites and increasing the use of fossil-free fuel, the goal of net-zero emissions can be approached. This can be done through coordinated orders and that the transport never leaves the construction site with an empty trailer. Colicchia et al. [18] describe measures and logistics solutions such as planning programs, speed limits, and reduced idling.

There is a large variety of fossil-free machines on the market today, such as a hydrogen-powered excavator by JCB, Volvo battery-powered machines, including loaders and excavators, and hydrogen-powered dump truck, the first of its kind in the world, etc. [13]. The European branch organization ACEA, together with Volvo, Scania, Daimler, Man, Daf, Iveco, and Ford, has taken a joint decision that commercial transport must be fossil-free by 2050 at the latest (ibid). Together, through the decision, they must find the best technology to reduce fossil use and develop the technology for fossil-free operation going forward [19].

Materials Management (e.g., sustainable material selection, waste reduction and recycling) is also a critical method to achieve more sustainable development in transport within the construction sector. To reduce the volume of waste on the construction site and increase the amount of waste per transport from the work site, Colicchia et al. [18] mention the use of compactors to compress the waste on site to reduce its volume. With the help of a compactor, the volume of the waste can be reduced by approximately 70–90% [13].

Stakeholder Collaboration (such as engagement of local communities, collaboration with authorities) can also support sustainable development of transportation. Construction sites can benefit from a third-party actor who manages the construction logistics. For example, a third-party logistician can take care of the construction site's machine and material planning, including, among other things, storage of materials and waste in and deliveries from the construction site, machines, orders, and planning [13, 20].

Monitoring and Evaluation (data collection and analysis, performance indicators and targets) can help identify areas for improvement and measure progress toward sustainability goals. For example, Ciliberti et al. [21] describe that ICT applications can analyze the choice of transport routes, optimal speeds depending on the vehicle and log idling runs. By adapting transport routes and speed according to road type, altitude levels, and distances, speed can be optimized to reduce acceleration and braking. Through ICT, idling can also be registered and reduced for each vehicle [13].

5.2.2 Digitalization in the Construction Sector

Digitalization plays an important role in promoting sustainable transport within the construction sector. By leveraging digital technologies, the sector can reduce its environmental footprint, enhance operational efficiency, and ensure compliance with sustainability goals. *Artificial Intelligence* (AI)[1] can analyze traffic patterns, weather conditions, and other relevant data to optimize transportation routes, reducing fuel consumption and emissions. AI-powered predictive maintenance can monitor the condition of vehicles and construction machinery, enabling early detection of potential issues. AI can also optimize the operations of construction equipment, such as cranes, excavators, and bulldozers, to minimize energy consumption while maintaining productivity. AI-powered sensors and monitoring systems can provide real-time data on construction sites, traffic conditions, and vehicle performance. However, it is essential to ensure that AI deployment is done ethically, responsibly, and with careful consideration of potential unintended consequences.

Next digitalization solution is *Building Information Modeling* (BIM).[2] BIM can facilitate the optimization of transportation routes, materials management, and logistics, leading to reduced energy consumption and emissions. BIM also enables stakeholders to visualize and analyze various design options and scenarios for transportation infrastructure projects. This includes road layouts, bridges, tunnels, and other transportation elements. BIM allows for energy analysis and simulation, helping design teams optimize the energy performance of transportation-related structures. It can assess factors like lighting, HVAC systems, and material selection to create more energy-efficient buildings, transport hubs, and maintenance facilities. BIM can be integrated with Internet of Things (IoT) sensors and real-time monitoring systems to track the performance of transportation infrastructure. This data helps identify inefficiencies and areas for improvement, leading to better resource utilization and sustainability.

Multi-Criteria Decision Making (MCDM) and *Geographical Information Systems* (GIS)[3] are used to assist in urban road planning [22]. The *digital twin* (DT)[4] concept

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[1] AI is <system> capability to acquire, process, create, and apply knowledge, held in the form of a model, to conduct one or more given tasks [28].

[2] BIM is a use of a shared digital representation of a built asset to facilitate design, construction, and operation processes to form a reliable basis for decisions [29].

[3] GIS is a computer system capable of assembling, storing (1) <placement>, manipulating, and displaying geographically referenced information, i.e., data identified according to their locations [30].

[4] Digital twin is a digital replica of physical assets (physical twin), processes, and systems that can be used for various purposes or a fit-for-purpose digital representation of something outside its own

can also provide a solution for road planning to digitalizing and interpreting the information in the physical world, including geometric and non-geometric information [23]. Different sectors have applied digital twin to realize many applications, e.g., manufacturing [24] and aerospace industry [25]. Also, digital twin has been employed in the construction sector, specifically in the design, construction stage, and operation and maintenance stages [23], since it can assist in decision making and designing (e.g., digital twin city [26]) in complex and sustainable urban road planning considering various factors including sustainability development [27].

Internet of Things[5] devices, such as sensors and telematics, can be deployed in vehicles, construction equipment, and infrastructure to collect real-time data on traffic flow, congestion, and vehicle movements. This data can be used to optimize transport routes, monitor fuel consumption, track vehicle maintenance, and promote efficient resource allocation. IoT-enabled devices can be installed in construction vehicles and transport fleets to monitor their performance, fuel efficiency, and maintenance needs.

Universal traceability of material items needs to depend on less complex and much less costly solutions to even in principle aim to individualize every material item. Carlsson and Elzén [27] describe the evolution of *Internet of Materials* concept (IoM)[6] following IoT. A general structure of IoM includes the material item (e.g., metal component) with some individualized communication aspect (e.g., QR code etched into the metal, antenna with individual resonance frequency—RFID) that can be read by some aspect communicator, such as an optical reader that both captures the QR code and identifies the material item. A material item in the IoM concept only has its identity. It is linked with its digital twin through this identity. IoM has several benefits to IoT as the solution for universal traceability such as fewer costs, easier to implement, and more sustainable choice since IoM-enabled material items only require energy when the item is created and when its data is requested, updated, or deleted. Such universal traceability and data sharing solution can help to provide efficient and effective material logistics, effective remanufacturing, reuse, and recycling, connect different sustainable business models in a variety of industries, nationally and internationally, control of critical materials flows, as well as quality control over the entire life cycle/several life cycles.

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context with data connections that enable convergence between the physical and virtual states at an appropriate rate of synchronization [31].

[5] Internet of Things is infrastructure of interconnected objects, people, systems, and information resources together with intelligent services to allow them to process information of the physical and the virtual world and to react [32].

[6] IoM is material items with digital identity and functionality, which utilizes computers and the internet for all computing, data storage, and sharing.

5.2.3 *Managing the Sustainability Performance of Transport Operations*

To be able to address both the multitude of different stakeholders, actors, and decision makers of the sustainability management of the construction sector's transports and the actual domain of control and information feedback of such management, in our research, have applied the two general models presented here.

Figure 5.1 shows examples of decision makers that need to have access to up-to-date sustainability data throughout a construction project, specifically the following:

1. The management of the construction project holds the responsibility both for how the contracted transports carry out and for performance targets where the construction operations do not exceed construction emission or noise thresholds.
2. The logistics planning department is responsible for the establishment of operational plans for how the sustainability requirements can be met while at the same time achieving the objectives.
3. For the operational construction and logistics managers to realize the plans according to performance restrictions, they need to have guidance and feedback via available information systems.
4. Transport purchasers are responsible for establishing clear contracts with transport providers, with regard to thresholds and performance targets, but also with regard to how to report data and verify compliance, e.g., which data forms and formats to use.

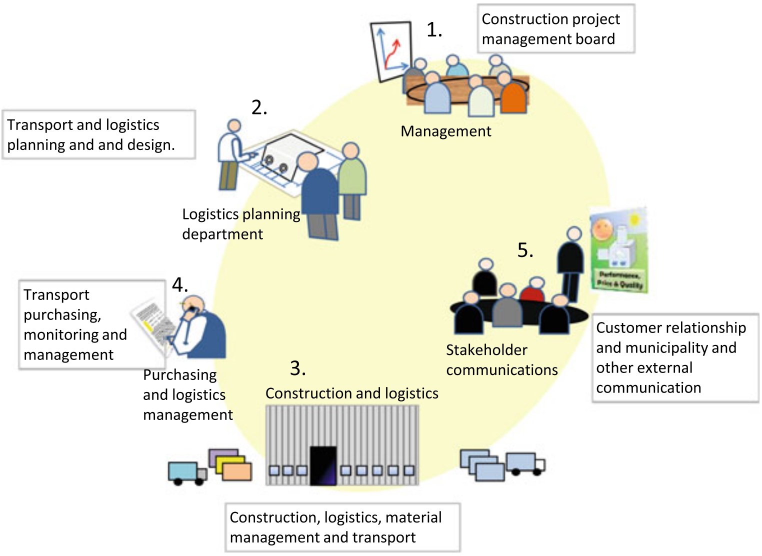

Fig. 5.1 Stakeholders of sustainability data (adapted from [3])

5. Key stakeholders of the sustainability information are legislators and the customer of the resulting construction. The overall transport compliance with laws and regulations and the sustainability performance of the total construction are of significance to citizens and the brand value of the final owner.

5.2.4 Control System

Figure 5.2 shows a simple, general control system, where the feedback loop provided by the information system feeds any decision maker (Fig. 5.1) with current, actual, and up-to-date information to relevantly and correctly control the performance of the system. The parts of the model are presented in Fig. 5.1.

Transports of a construction project that demonstrates all transports within the mandate of the management of a construction project. The 'box' may also represent any partial transport or segment of the route, depending on who is the decision maker.

Target value is a threshold value that does not exceed any other sustainability performance values.

Measurements made somewhere throughout the entire system of transport, such as goods, distances, emissions, and fuel use.

Current direction, i.e., current sustainability performance, operates.

Information System, i.e., channeling information relevant to the decision maker.

Information that is acquired from the measurement of transports is calculated and compiled to mediate meaningful information to decision maker(s).

Decision Maker: in this context, any of the five different decision makers introduced in Fig. 5.1.

Control is a mandated response from a decision maker intended to align the results in the system *Transports of a construction project* to the target.

Section 5.3 presents how a combination of the data format standard BEAst, and in particular BEAst Eco, and the ISO 14033 standard for acquiring and compiling the information may be used to establish the information system in Fig. 5.2 to coherently, flexibly, effectively, and efficiently provide relevant information to the decision makers exemplified in Fig. 5.1.

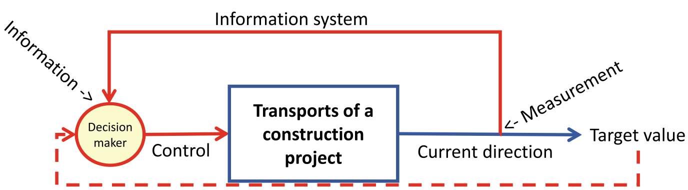

Fig. 5.2 Control system for a well-designed digitalized management information system for transports of a construction project

5.3 Methodology

Having performed literature review for solutions that support digitalization of the sustainability management of the construction sector's transports, we conclude that the data exchange standard BEAst and its international match PEPPOL enables the exchange of data between actors of both the transport and the construction sectors. However, though both these standards to different degrees generally support sustainability data, neither of them is developed to handle such data to support the different systems levels of the construction sector. Therefore, it was concluded that merging the BEAst/PEPPOL formats with the internationally standardized framework for quantitative environmental data, ISO 14033, is a possible way to proceed.

The two standards that are here combined are developed within two different contexts and for different purposes. They are presented in the next sections.

5.3.1 BEAst Standard

The BEAst standard is a standard format for the construction sector's data exchange, in particular concerning business and logistics transactions. BEAst[7] stands for 'The Construction Industry's Electronic Business Standard.' It is a network of just over 100 leading companies and organizations from various parts of the construction sector that work together in a non-profit association to develop common standards and methods for digital communication in collaboration with Nordic and international organizations. The focus is on the processes for procurement, purchasing, logistics, and invoicing [9].

Of particular interest for sustainability management is that BEAst includes the component BEAst Eco, which is a special module intended to follow up on fuel consumption and emissions from deliveries, such as climate data. The purpose of BEAst Eco is to track environmental loads from transports to and from construction sites. BEAst Eco can support reporting how far a vehicle has driven, what kind of fuel has been consumed, and the environmental classification of the engine. Table 5.1 shows that the BEAst Eco has pre-specified entries for emissions of carbon dioxide, particles, nitrogen oxide, and more.

BEAst Eco does not specify how the data that is entered into the system should be measured, calculated, or compiled. The format allows for the data to be calculated in any way the user wants. This means that data could equally well represent only the last transport leg or a full transport contract. This is a strength regarding the flexibility of the format used, but it also gives room for misunderstanding and needs for further standardization. Therefore, to make use of this flexibility in the BEAst Eco data message format, the authors suggest to combine it with the standard for quantitative environmental information, presented in the next subsection.

[7] In Swedish: 'Byggbranschens Elektroniska Affärsstandard'.

Table 5.1 BEAst eco specification of emissions from the transport vehicle

Elements and structure				
Term nbr	Element	Occ	Specification	
T6375	Carbon dioxide	0.1	Definition	Total amount of CO_2 eq.
			Format	XSD Decimal
			Tag	Carbon dioxide
T6376	Nitrous oxide	0.1	Definition	Total amount of NO
			Format	XSD Decimal
			Tag	Nitrous oxide
T6377	Particle matter	0.1	Definition	Total amount of NO
			Format	XSD Decimal
			Tag	Particle matter
T6378	Carbohydrates	0.1	Definition	Total amount of emitted hydrocarbons
			Format	XSD Decimal
			Tag	Carbohydrates
T6379	Engine type	0.1	Definition	EU Environmental engine class, e.g., 'Euro 6'
			Format	String 17
			Tag	Engine type

5.3.2 ISO 14033 Environmental Management—Quantitative Environmental Information—Guidelines and Examples

The international standard ISO 14033 on quantitative environmental information [10] provides a general structure for quantitative systems analytical information. The framework was initially developed to fill the gap between different quantitative environmental management's systems analytical methods and their dependence on and relationships with metrological facts and data [33–35]. These research results (between 2008 and 2019) were further developed within ISO[8] into a standardized framework to guide the acquisition, compilation, reporting, or verifiability of quantitative data for purposes of environmental or sustainability management, particularly for, but not limited to, the standards of the ISO 14000 series.

Figure 5.3 represents the ISO 14033 standardized framework. Horizontally, the framework is divided into three parts, starting to the left with *Requirements of the objective* and ending to the right with *Meeting the objective*. In the center lies the *Realization of objective*—the emphasis of the framework. The central part of the

[8] ISO—International Standards Organization/Technical Committee 207/Environmental management.

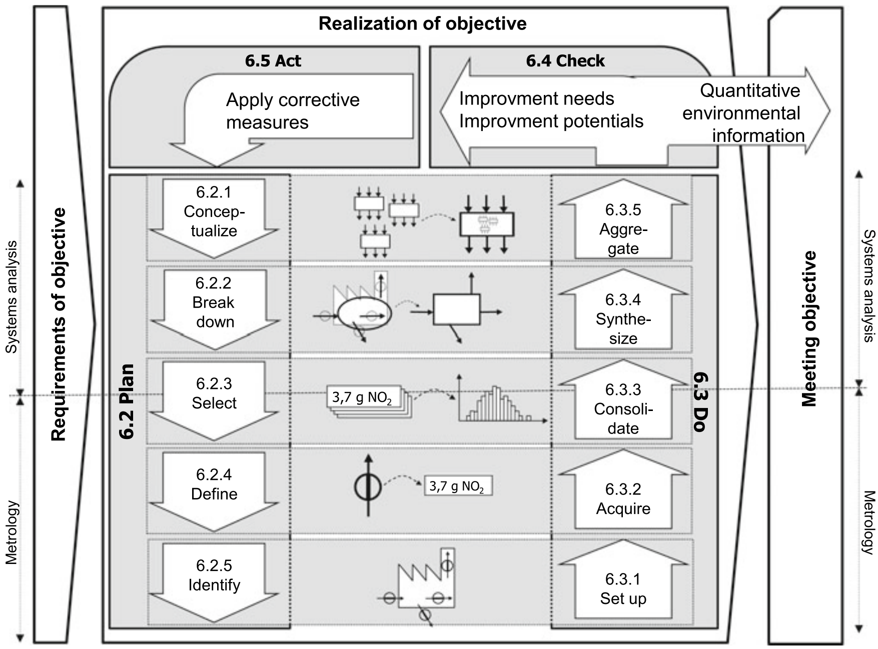

Fig. 5.3 Framework of ISO 14033—Quantitative environmental information (adapted picture from [10])

framework is based on a Plan-Do-Check-Act model.[9] The intention is that information acquisition projects or information systems designed for sustainability management are naturally evolved and iteratively improved along with the build-up of experiences and due to increased requirements. Both the Plan- and Do-stages consist of five matching steps. The Plan-stage goes top-down, starting at the top with interpreting and conceptualizing the requirements for the information to acquire, and ending at the bottom with specifying which data is needed and providing specifications for the measurement system. The Do-stage goes bottom-up, starting with the measurement system and the acquisition of data, and then stepwise follows what has been planned for the statistical handling of acquired data, the synchronization of data originating from different measurement systems, and the eventual calculation, compilation, and communication of the resulting information. One practical consequence of the framework is that it shows how to bridge fact-based data taken from any data source or measurement and stepwise establish a higher system level of fact-based data without losing verifiability. The framework is simple and potentially universal and hence can serve as a template for any information acquisition compilation and reporting project or system with ambitions to maintain verifiability.

[9] Note that it turns counterclockwise.

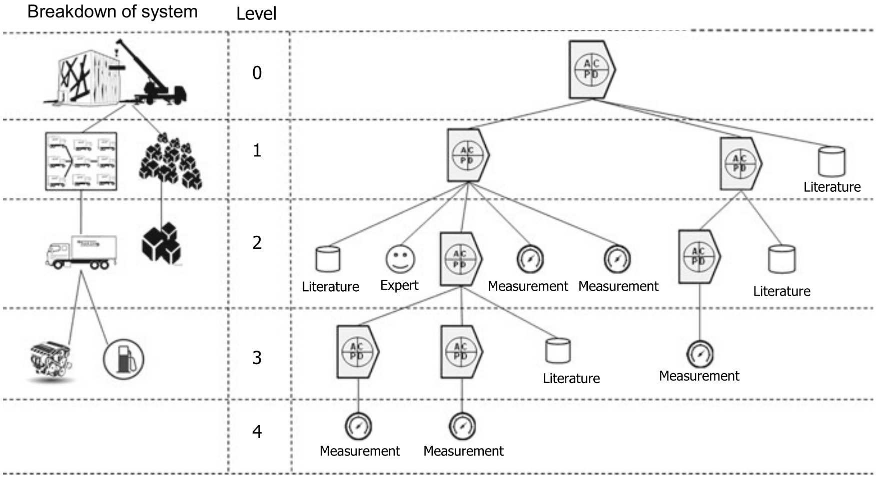

Fig. 5.4 Applying the framework of ISO 14033 for transparent and verifiable information systems design. Picture adapted for the context of this research. (The symbol with the letters PDCA represents the framework in Fig. 5.3)

Figure 5.4 shows how the framework in the standard ISO 14033 can repeatedly be used to establish transparent and verifiable information reporting routines or information systems. From the bottom-up, the figure represents how data from different data sources are aggregated into stepwise higher system levels. From the top-down, the figure may represent either a breaking down of information into its need for basic data sources (measurement, literature, or expert), or a review of a report into its fundamental data and data treatment [36].

5.3.3 *Combining BEAst Eco and ISO 14033*

BEAst Eco is a standardized structure for messages for the exchange of environmental data about transports related to construction projects within the practically applied BEAst data exchange standard. The standard allows equally well very detailed or very aggregated environmental data, from engine parameters, good weight or volume or transport route positions, up to environmental data about the transport supplier company or an entire construction project. Partly due to this flexibility of the format, the BEAst Eco message has no specified requirements or guidelines for how the environmental data should be measured or otherwise prepared before being entered into a BEAst eco message. The framework and intended application of the ISO 14033 standard are based on system aggregation flexibility. It handles equally well any detailed directly measured data from, for example, the real-time fuel consumption of a truck, as it manages total reporting of all emissions from all transports of a transport company or a construction project. In addition, ISO 14033 also provides guidance on how to structure specifications for how environmental data should be measured and prepared. Therefore, it is of great value for construction sector's sustainability management if these two standards are combined into one single specification where ISO 14033 guides how sustainability data shall be specified when communicated to a specific decision maker, and BEAst Eco indicates the format for digital exchange of sustainability data between decision makers in the construction sector.

5.4 Top-Down and Bottom-Up Mapping for Strategic Digitalization

Digitalization needs and opportunities are mapped from a *top-down* perspective, from top management[10] down to individual data sources, represented by vehicle sensors and a combination of sector-based, company-based, and technology and project-specific databases (Sect. 4.1), and from a *bottom-up* perspective, where various existing data sources are assessed, linked in, and mapped with regard to the value of their information content from the viewpoint of key transport sustainability decision points (Sect. 4.2). These two vertical directions of mapping to connect decision making with data sources are done with the intentional purpose of utilizing digitized data to provide decision-making people and machines with relevant information for both strategic and real-time sustainable management of all transports related to a construction project.

5.4.1 A Top-Down Perspective: Realizing the Need for Data and Digitalization

The circled numbers (1)–(4) in Fig. 5.5 show the order, in which to carry out a top-down mapping for setting up a sustainability management information system that fulfills the needs at different decision points throughout the construction site transport system: (1) identifies total aggregated sustainability information needs for all construction project transports; (2) breaks down the total transports into relevant categories, such as per good type and supplier; (3) identifies what measured and otherwise acquired data is needed to meet the information needs and specifies calculation routines for aggregation of data at each level, and (4) documents measurement points and calculation routines using the ISO 14033 structure, implements calculation and data transfer routines into different appropriate software systems, stores

[10] Here, top management represents the ultimate user for the digitalized information, to emphasize that all information ultimately benefits the sustainability performance of a total construction project. However, most collected data will be aggregated, interpreted, and acted upon before reaching top management.

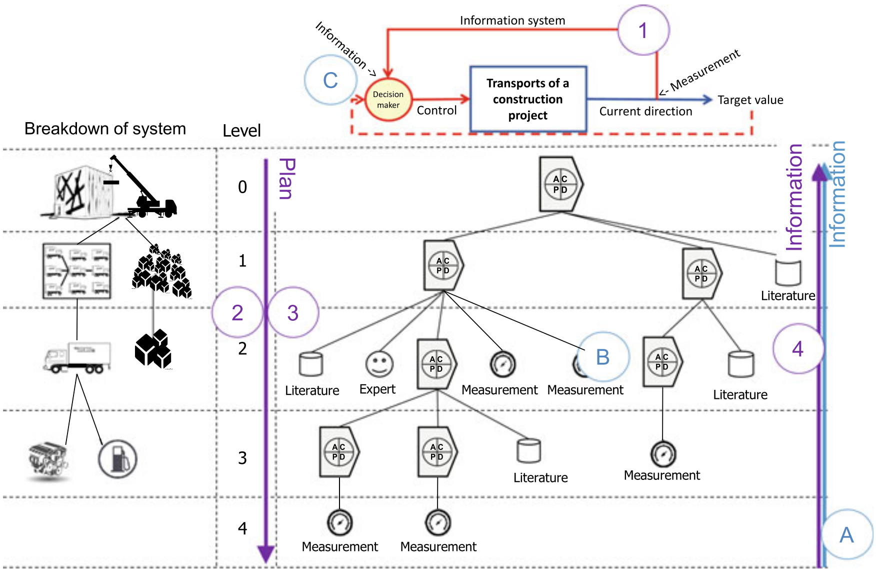

Fig. 5.5 Top-down (1–4) and bottom-up (A–C) view of information system design strategy

calculated data and references to document into the BEAst Eco format, and utilizes appropriate network technology to forward the data and to realize the system design.

5.4.2 *A Bottom-Up Perspective: Take Advantage of Existing Data*

The light blue-circled letters (A)–(C) in Fig. 5.5 represent viewpoints, from which to carry out a bottom-up investigation of how to utilize and digitalize data from already available measurements, data registers, or administrative systems throughout the different transport systems of a construction project: (A) maps existing data and register their data specification and registration quality, level of digit readiness, system interconnectedness, data format, etc.; (B) examines how data could be shared, communicated, and be made understandable, together with a rough estimate of the cost of such work at different decision levels; (C) performs a utility-based cost–benefit analysis for making the information available for decision making and control at different decision points throughout the transport system.

5.5 Conclusion and Recommendations

The research has provided new concepts, terms, and possibilities to describe digitalization status, gaps, and potential designs, as well as the possibility to analyze the potential of information system modules before they are implemented. In particular, it demonstrates how to graphically show which data is under-utilized or missing and which data is considered useful.

This research has shown that the combination of the two standardized structures of BEAst Eco and ISO 14033 provides highly versatile building blocks for a management system for strategic digitalization. It not only combines individual organizations' need to strategically handle their data, but also merges the requirements to achieve verifiable statements to regulators and for market claims, as well as provides the bridge to high-quality GIS positioning data about different sustainability issues, as well as more fundamentally enabling digitalized sustainability management support, such as through statistical data based on sensor networks in transport equipment, goods, and infrastructure. By applying the framework of ISO 14033 for top-down and bottom-up vertical digitalized data acquisition and flow and the BEAst standard for horizontal data networking and exchange, it was shown how to facilitate digitalization for transparent data-driven sustainability management of construction transports, including strategically efficient multi-use of data.

The Plan-Do-Check-Act loop of ISO 14033 is the driver for continual improvement and may be the core of a digitalization strategy management system. Most construction companies already work with management systems based on a fact- and decision-based continual improvement process, similar to a Plan-Do-Check-Act. They can, therefore, recognize and seamlessly adapt the proposed management system structure based on either top-down or bottom-up gradual system improvement models. A gradual implementation immediately puts the digitalization strategy into effective use by engaging everyone from the operational to the strategic level and all in between throughout the organization.

Integration of the standards is intended to not only be made within individual organizations or projects but to be a part of the construction sector's transformation to higher efficiency, quality, and sustainability performance. Therefore, both a formal harmonization and a practical harmonization need to be done, preferably implemented as a formal standard with broad consensus throughout the sector. In addition, a fruitful implementation should encompass not only the transport but also the total construction projects. It is worth noting that in 2022, the BEAst standard was mapped onto the PEPPOL[11] standard [37], which implies that the work presented in this article has a more universal and global value than was originally intended.

[11] Pan-European Public Procurement Online.

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Chapter 6
Managing Circular Electric Vehicle Battery Lifecycles Using Standards

Raul Carlsson and Tatiana Nevzorova

Abstract The electric vehicle (EV) market and its implied battery resource management are in large and fast expansion. The European Union is developing directives for digital product passport for batteries, where much understanding and knowledge of battery management are quickly growing. Coordinating standards that can harmonize circular battery management and spread best practices is therefore in high demand. This research presents a review of existing standards that support managing circular EV battery lifecycles. It was performed to understand the maturity of the circular battery lifecycle, regarding battery performance and safety to workers, EV passengers, and the environment. The review structure was made by positioning standards to key steps throughout the circular battery lifecycle, highlighting steps where handling, producing, testing, servicing, and remanufacturing could be expected to support harmonization and guidance. The scope was limited to mainly lithium-ion batteries for vehicle traction but also included general standards concerning recycling, safe battery handling, and environmental management. The resulting mapping summarizes a catalog of existing and upcoming standards. It shows that many important standards are available. Much still needs to be developed, especially with regard to tests for reused batteries' health and performance and with regard to how to synchronize performance specifications along and across the circular life cycle stages. To the best of the authors' knowledge, this study is the first attempt to provide such a comprehensive overview of standards that covers the whole circular electric vehicle battery lifecycles.

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6.1 Introduction

With the transition to an electrified vehicle fleet, batteries are crucial in the deployment of zero-emission mobility and intermittent renewable energy storage, and in the EU's transition to a climate-neutral economy [1, 2]. For example, the number of electric vehicles (EVs) is increasing every year in Sweden. In 2021, a total of 57,469 electric cars, 22,196 electric hybrids, and 77,847 plug-in hybrids were registered. By comparison, in 2016, 2775 electric cars, 13,501 electric hybrids, and 9816 plug-in hybrids were registered [3]. Increased electrification is in line with Sweden's goal of creating a fossil-free vehicle fleet. However, there is a risk that the environmental benefits of the transition could be diluted if we do not plan for sustainable and safe management of batteries at the end of their first life in an electric vehicle. With an increasing number of EV batteries on the market, there is a growing need for increased effectiveness and efficiency of circular flows of batteries from EVs. It is especially important to ensure that batteries and their components are reused and recycled since batteries contain valuable and critical materials such as cobalt, lithium, and nickel which risk being in short supply in the near future.

A sustainable and circular value chain for EV batteries reduces environmental impact and the extraction of natural resources to maintain an environmental balance while promoting economic growth [3]. Moving from a "traditional" linear model to a circular value chain will enable the battery economy to become resource efficient. Standardized and safe processes, methods, and tools facilitate the correct diagnosis of batteries, allowing a better assessment of the status of the battery and whether it should be reused or recycled. Reuse can take place either as a component in another vehicle or as part of another application, e.g., energy storage. Through an efficient value chain with safe handling and good analysis, the economic value of batteries can be better utilized. In this way, the automotive industry can contribute to ecosystems and business models being better adapted to circular and sustainable systems [4]. In addition, a well-organized flow with clear roles and safe practices can help to better regulate the market. Therefore, this research aims to establish new and expanded knowledge by reviewing and analyzing international standards that could facilitate increased circular use of batteries as well as academic literature that focuses on the harmonization of standards in this field. The results of the paper aim to contribute to and accelerate a shift toward safe processes and efficient value chains better adapted to circular and sustainable systems. The overall goal is to support the ecosystem's actors in their shared efforts to achieve circular, sustainable, and safe processes for vehicle batteries. This gives better prerequisites and a basis for business development in harmony with increased electrification.

6.2 Methodology

6.2.1 Review of Academic Literature and Existing Standards

Standardization has been recognized by the European Commission as the foundation of the single market and global competitiveness and as the key to scaling up the implementation of innovations [5]. International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) are both global, non-profit membership organizations, whose work underpins quality infrastructure and enables international trade. These standards are openly available, internationally neutral and adopted, sector independent, and are in operative use worldwide. This paper presents the research based on already existing building blocks, established on formal international agreements, specifically ISO and IEC standards, and reviews the scholarly literature that focuses on the harmonization of the standards.

Two rounds of data selection were conducted. The first round of data collection includes the extraction of scholarly literature using the Scopus database. Different kind of keywords and synonyms were used to retrieve as many relevant publications as possible. The combination of keywords such as (EV∗ OR electric vehicle batter∗ OR EV batter∗) AND (standard∗) was applied and searched in the topic area, i.e., the abstracts, titles, and keywords. In the initial step, 47 publications were extracted. In the next step, the full texts were evaluated in detail for their relevance to the analyzed topic. The first round of the data collection process resulted in 12 publications.

Second round includes the extraction of existing standards using ISO (https://www.iso.org/obp/ui/en/) and IEC (https://www.iec.ch/publications/international-standards) databases. This round includes several iterative processes. The main combinations of keywords such as "electric vehicle" and "battery" were used. Also, the authors further analyzed the separate families of standards and standardization expert working groups that work on circular life cycle, remanufacturing, reuse, recycling, and waste management. We believe that such additional analysis helps to enlarge and propose specific standards for making more circular life cycle of EV batteries. In addition, the standards that were found in scholarly literature were checked in the ISO and IEC databases to verify their status and validity and update the standard version if the new one was established.

6.2.2 The Proposed Concept of the Circular Life Cycle of EV Batteries

Closing an effective and efficient reverse circular battery reuse and remanufacturing loop is of essential significance. A key to this is to step by step establish links of safe handling of post-use batteries, from use-phase to well-specified and quality-assured reuse and remanufacturing. To achieve such a reverse path of safe links, it is necessary to identify and manage all risks throughout the reverse loop. This is an ongoing research domain, where some risk areas are already known and managed at the current best knowledge, but where much uncertainty remains. Figure 6.1 introduces the graphical tool to support the research. The two yellow boxes at the top represent a general *Battery producer* and vehicle *Original Equipment Manufacturer* (OEM). All actors in the model are represented concerning how they share the same specifications while producing, handling, and trading with batteries and battery materials. The green box at the bottom right, *Preparing for reuse*, depicts how after-use batteries comply with specifications as safe and functional batteries ready to be returned to the market. The pink box at the left–right, *Preparing for remanufacturing*, represents how batteries and dismantled battery components are screened, tested, and sorted out for reuse, recycling, or remanufacturing after being tested for compliance with specifications for battery manufacturing components. The orange straight lines with right-angle corners represent batteries and battery materials flow between the three stages of the circular battery life cycle. The red, curvy dotted lines describe how specifications are set across the same life cycle to ensure battery safety and quality performance.

The eight small, yellow boxes with orange frames and numbered texts in Fig. 6.1 represent the areas of special concern where much formal standards exist and where ongoing standardization projects in different standard bodies occur but where many crucial standards are still lacking. Each of the eight boxes represents the specific type of challenges where these standards are of particular value. Summarizing, the research seeks to compile and structure the existing standards and ongoing standardization work that addresses the circular life cycle of batteries and battery material with a focus on reuse and remanufacturing. This is done in two steps. First, by reviewing the existing and ongoing standardization work in the area. Second, by

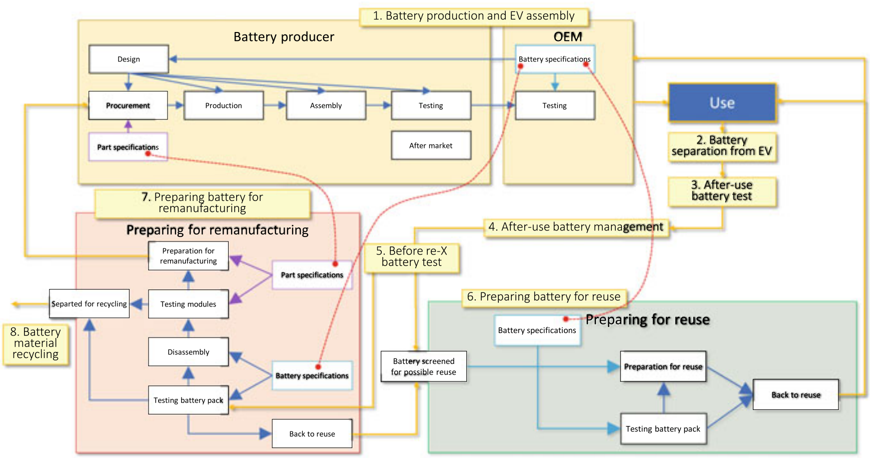

Fig. 6.1 A simplified view of the circular life cycle of batteries and battery material with a focus on reuse and remanufacturing

seeking to arrange the value of these standards throughout the circular battery life cycle depicted in Fig. 6.1.

6.3 Results

6.3.1 Battery Production and EV Assembly

Several standards guide how the performance and reliability of the resulting batteries are specified, and there are also standards that guide the battery production and EV assembly. Together these standards lead to safe and reliable processes to meet standardized performance specifications. Formal standards are established by various organizations, e.g., the International Organization for Standardization, the Society of Automotive Engineers (SAE), and the Institute of Electrical and Electronics Engineers (IEEE). Overall, adherence to these standards and regulations is critical to ensure that battery production and EV assembly are safe, reliable, and meet the high-quality requirements of the electric vehicle industry. In the following sub-sections, the different standards that are related to the (1) battery production and EV assembly in Fig. 6.1 are presented and analyzed.

6.3.1.1 Battery Production and EV Assembly—Battery Producer

Traceability and consequently identifiability are crucial for closing the circular life cycle of EV batteries. This is because data sharing enables efficient use of materials, and components, knowledge of battery design, component manufacturing, service, disassembly, reuse, remanufacturing, second use, and recycling. For example, the project BatteryPass specifies the following identification of EV batteries [6]:

- *Battery unique identifier* that allows for the unambiguous identification of each battery and hence each corresponding battery. The unique identifier shall comply with the standard ISO/IEC 15459:2015 [7].
- *Manufacturer's identification*, i.e., unambiguous identification of the manufacturer of the battery, suggested via a unique operator identifier.
- *Manufacturing date* (month and year) in the form of manufacturing date codes.
- *Manufacturing place* (e.g., country, city, street, building (if needed)) suggested via a unique facility identifier.

Further specific examples of standards for the Battery Producer are the following:

- *EN 6429:1996/corrigendum Oct. 1998* Marking of secondary cells and batteries with the international recycling symbol ISO 7000-1135 and indications regarding directives 93/86/EEC and 91/157/EEC.

- *EN IEC 62902:2019* Secondary cells and batteries—Marking symbols for identification of their chemistry, guiding color codes and QR codes to direct waste stream of different battery technologies on the market [8].
- *CE Marking certification* ensures that battery packs and EVs meet safety and performance standards in the European Union [9].

Several standards govern battery production and EV assembly, which ensure that these processes are safe, reliable, and meet certain quality requirements. Here is a list of some of the most important standards in these areas:

- *ISO 26262:2018* Functional Safety standard that provides guidelines for the functional safety of safety–critical systems in vehicles, such as battery management systems [10].
- *UN 38.3* Transportation Testing standard provides guidelines for testing lithium-ion batteries to ensure safe transport [11].
- *UL 1642* standard provides guidelines for the safety of lithium-ion batteries [12].
- *EN 50604-1:2016/A1:2021* Secondary lithium batteries for light EV (electric vehicle) applications—Part 1: General safety requirements and test methods [13].
- *EN IEC 62660-1:2019* Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 1: Performance testing [14].
- *EN IEC 62660-2:2018* Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 2: Reliability and abuse testing [15].
- *SAE J2464_202108* Electric and hybrid electric vehicle rechargeable energy storage system (RESS) safety and abuse testing [16].
- *SAE J2929_201302*. Safety standards for electric and hybrid vehicle propulsion battery systems utilizing lithium-based rechargeable cells [17].
- *ISO 6469-1:2019*. Electrically propelled road vehicles—safety specifications—Part 1: Rechargeable energy storage system (RESS) [18].
- *ISO 12405-4:2018*. Electrically propelled road vehicles—test specification for lithium-ion traction battery packs and systems—Part 4: Performance testing [19].
- *IEC 62660-3:2022 RLV*. Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 3: Safety requirements [20].
- *IEC 63369-1 ED1*: Methodology for the Carbon Footprint calculation applicable to lithium-ion batteries (under development) [21].

6.3.1.2 Battery Production and EV Assembly—OEM

Specific examples of standards for the EV Assembly Standards, OEM:

- *ISO 9001:2015* provides guidelines for quality management systems [22].
- *ISO 14001:2015* provides guidelines for environmental management systems [23].
- *EN IEC 62485-1:2018* Safety requirements for secondary batteries and battery installations—Part 1: General safety information [24].

- *EN IEC 62485-3:2014* Safety requirements for secondary batteries and battery installations—Part 3: Traction batteries UN R100 regulation: safety requirements for electric powertrain systems, including battery packs and electric motors [25].
- *EN IEC 62660-3:2022* Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 3: Safety requirements [20].
- *ISO 6469-1:2019*. Electrically propelled road vehicles—safety specifications—Part 1: Rechargeable energy storage system (RESS) [18].
- *ISO 6469-2:2022*. Electrically propelled road vehicles—safety specifications—Part 2: Vehicle operational safety—a two-part standard to help manufacturers design fail-safe EVs [26].
- *ISO 16750-3:2012* Road vehicles—environmental conditions and testing for electrical and electronic equipment Part 3: mechanical loads [27].
- *SAE J2380_202112* Vibration testing of electric vehicle batteries [28].
- *SAE J-2929_201102* is related to the safety of the propulsion battery system [17].
- *SAE J-2344_202010* defines rules for EV safety [29].
- *SAE J-2910_201404* electrical safety of buses and test for hybrid electric trucks [30].
- *SAE J-2464_202108* defines the safety rules for recharge energy storage systems (RESS) [16].

Overall, we can conclude that many standards for battery production and EV assembly already exist and continuously being updated. However, for example, the area of traceability and supply chain should be improved. Ensuring transparency and traceability in the battery supply chain is essential to address concerns related to human rights, labor practices, and raw material sourcing. Developing standards that promote ethical sourcing, responsible manufacturing practices, and traceability can support a sustainable and socially responsible battery industry.

6.3.2 Battery Separation from EV

Several standards govern the safe handling and disposal of lithium-ion batteries when they are separated from EVs. They ensure that batteries are handled to minimize the risk of injury, fire, or environmental damage. Some examples of standards are:

- *ISO 15270:2008* provides guidelines for the management of end-of-life vehicles, including the safe handling and disposal of lithium-ion batteries [31].
- *IEC TS 62840-1:2016* Electric vehicle battery swap system—Part 1: General and guidance [32].
- *IEC 62840-2:2016* Electric vehicle battery swap system—Part 2: Safety requirements [33].
- *IEC PAS 62840-3:2021* Electric vehicle battery swap system— Part 3: Particular safety and interoperability requirements for battery swap systems operating with removable RESS/battery systems [34].

- *ISO 6469-4:2015* Electrically propelled road vehicles—safety specifications Part 4: post-crash electrical safety requirements [35].
- *IEC 62933-5-3 ED1* Electrical energy storage (EES) systems Part 5-3: Safety requirements when performing unplanned modification of electrochemical based EES systems (under development) [36].

The manual to remove the battery is important to have for safety, proper procedure, maintenance, etc. For example, the manual to remove the battery from the appliance should include disassembly sequences; characteristics of the joints, screws, and fasteners; tools required for disassembly, risk warnings, and safety measures [6]. Another manual can be for disassembly and dismantling of the battery pack and include exploded diagrams of the battery system/pack showing the location of the battery cells and modules; type of construction of battery pack, modules, and cells; information on replaceability of modules and cells; disassembly sequences; characteristics of joints, screws, and fasteners; information on fillings and casing; tools required for disassembly, risk warnings, and safety measures [6].

6.3.3 After-Use Battery Test

Several standards govern the testing of after-use EV batteries to guide the handling of after-use batteries:

- *EN 50604-1:2016/A1:2021* Secondary lithium batteries for light EV (electric vehicle) applications—Part 1: General safety requirements and test methods [13].
- *EN IEC 62660-1:2019* Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 1: Performance testing [14].
- *EN IEC 62660-2:2018* Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 2: Reliability and abuse testing [15].
- *EN IEC 62660-3:2022* Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 3: Safety requirements [20].
- *ISO 6469-4:2015* Electrically propelled road vehicles—safety specifications Part 4: post-crash electrical safety requirements [35].

6.3.4 After-Use Battery Management

The transportation of after-use EV batteries is subject to several standards and regulations that are critical to ensure that after-use EV batteries are transported safely and without posing a risk to human health or the environment. These standards are:

- *UN Model Regulations on the Transport of Dangerous Goods* provides guidelines for the safe transport of lithium-ion batteries [37].
- *UL 2580:2022* standard provides guidelines for the safety of energy storage systems, including lithium-ion batteries that are removed from an EV.

- *SAE J2464_202108* standard provides guidelines for the transportation, storage, and recycling of lithium-ion batteries [16].
- *IEC 62933-2-1:2017* standard provides guidelines for the safe transportation of second-life batteries including after-use EV batteries, for use in energy storage systems [38].
- *UN 38.3* Transportation Testing for Lithium Batteries and Cells focuses on parameters for how you should comply with relevant rules regarding the transportation of lithium batteries by air, including testing, documentation, and labeling [11].

6.3.5 Before Re-X Battery Test

There is often uncertainty about how the first user may have handled and maintained the battery. To decide on which next re-X step for after-use batteries to take, further tests need to be made. Such tests are:

- *IEC 63330 ED1*—Requirements for reuse of secondary batteries (under development) [39].
- *EN 50604-1:2016/A1:2021*—Secondary lithium batteries for light EV (electric vehicle) applications—Part 1: General safety requirements and test methods [13].
- *IEC 62933-5-3 ED1*—Electrical energy storage (EES) systems Part 5-3: Safety requirements when performing unplanned modification of electrochemical based EES systems (under development) [36].
- *IEC 62660-1:2019*—Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 1: Performance testing [14].
- *IEC 62660-2:2018* Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 2: Reliability and abuse testing [15].
- *IEC 62660-3:2022 RLV*—Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 3: Safety requirements [20].

International standards that relate to the overview of tests in standards and regulations applicable to lithium-ion batteries in automotive applications are the following:

- *SAE J2464_202108*. Electric and hybrid electric vehicle rechargeable energy storage system (RESS) safety and abuse testing [16].
- *SAE J2929_201302*. Safety standards for electric and hybrid vehicle propulsion battery systems utilizing lithium-based rechargeable cells [17].
- *ISO 6469-1:2019*. Electrically propelled road vehicles—safety specifications—Part 1: Rechargeable energy storage system (RESS) [18].
- *ISO 12405-4:2018*. Electrically propelled road vehicles—test specification for lithium-ion traction battery packs and systems—Part 4: Performance testing [19].
- *IEC 62660-2:2018*. Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 2: Reliability and abuse testing [15].
- *IEC 62660-3:2022 RLV*. Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 3: Safety requirements [20].

- *ISO 16750-3:2012*. Road vehicles—environmental conditions and testing for electrical and electronic equipment Part 3: mechanical loads [27].
- *IEC 60068-2-64:2008/A1:2019*. Environmental testing Part 2: test methods—test Fh: vibration, broad-band random (digital control) and guidance [40].
- *SAE J2380_202112*. Vibration testing of electric vehicle batteries [28].

EV batteries can have valuable secondary applications after their use in vehicles. Standards can help guide the evaluation, refurbishment, and repurposing of used batteries for various applications, such as energy storage systems. These standards can address safety considerations, performance requirements, and the proper assessment of battery health for second-life use.

6.3.6 Preparing Battery for Reuse

The possibility of battery reuse should be evaluated before recycling. The question of whether reuse is possible or not is highly dependent on the state of health of the battery. Preparing an EV battery for reuse involves several steps, including testing, cleaning, and refurbishing the battery. At each step, there may be several safest and otherwise best ways to perform a test, a dismantling step, or a refurbishment step.

The list below presents different standards that are related to the numbered text 6 in Fig. 6.1 are presented and analyzed:

- *EN IEC 62619:2022*—Secondary cells and batteries containing alkaline or other non-acid electrolytes—safety requirements for secondary lithium cells and batteries, for use in industrial applications: provides guidelines for the testing of second-life batteries, including EV batteries that are prepared for reuse [41].
- *IEC 62660-1:2019*—Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 1: Performance testing: provides guidelines for the testing of automotive lithium-ion battery packs, including testing of electrical, thermal, and mechanical characteristics [14].
- *SAE J3072:2021* Interconnection Requirements for Onboard, Grid Support Inverter Systems: provides guidelines for the testing of used lithium-ion batteries from electric vehicles, including testing of capacity, power, and impedance before they are prepared for reuse [42].
- *IEC 62485-1:2015* Safety requirements for secondary batteries and battery installations—Part 1: General safety information [24].
- *EN IEC 62485-3:2014* Safety requirements for secondary batteries and battery installations—Part 3: Traction batteries [25].
- *IEC 63330 ED1* Requirements for reuse of secondary batteries (under development) [39]
- *IEC 62933-5-3 ED1* Electrical energy storage (EES) systems Part 5-3: Safety requirements when performing unplanned modification of electrochemical based EES systems (under development) [36].

- *IEC 63338 ED1* General guidance on reuse and repurposing of secondary cells and batteries (under development) [43].

Adherence to these standards is critical to ensure that the batteries are tested thoroughly, refurbished to meet necessary performance requirements, and safe for use in energy storage or other applications.

6.3.7 Preparing Battery for Remanufacturing

Preparing an EV battery for remanufacturing involves several steps. It is important that the remanufacturing is performed safely and with high quality. The list below presents different standards that are related to the numbered text 7 in Fig. 6.1 are presented and analyzed.

- *IEC 62660-3:2022 RLV*. Secondary lithium-ion cells for the propulsion of electric road vehicles—Part 3: Safety requirements: provides guidelines for the disassembly, refurbishment, and reassembly of lithium-ion battery packs from electric vehicles [20].
- *IEC 62933-5-3 ED1* Electrical energy storage (EES) systems Part 5-3: provides safety requirements when performing unplanned modification of electrochemical based EES systems [36].
- *ISO 14001:2015* Environmental management systems standard provides guidelines for the testing of used lithium-ion batteries from EVs, including testing of capacity, power, and impedance before they are prepared for remanufacturing [23].

6.3.8 Battery Material Recycling

This research has not specifically considered the material recycling of EV batteries. High-quality material recycling is essential for resource-efficient circular EV batteries. The two standards listed here are general management system standards related to any industrial processes, here associated with numbered text 8 in Fig. 6.1.

- *ISO 14001:2015* Environmental management systems standard provides guidelines for environmental management systems, including the management of hazardous waste generated during the recycling process [23].
- *ISO 50001:2018* Energy management systems—requirements with guidance for use standard provides guidelines for energy management systems, including the optimization of energy use during the recycling process [44].

A set of standards that can support the transition toward a circular economy is currently developing under technical committees ISO/TC 323 Circular economy (https://www.iso.org/committee/7203984.html). These standards are not specific for battery field. However, they can provide some guidance and supporting tools for the implementation of organizations involved in battery re-X to maximize the contribution to sustainable development. In addition, regarding traceability, we are well aware of the ongoing standardization of battery product passports, which is currently being implemented in line with the commission's Circular Economy Action Plan [45]. The projects BatteryPass [6] and CIRPASS [46] are preparing for this implementation, and a new standardization committee under CEN is being negotiated in EU while this paper is written.

Summarizing the results of the review of standards for battery reuse, remanufacturing, and recycling, we can conclude that the areas of sustainability and environmental impact of EV batteries are not sufficiently investigated. Thus, the development of standards addressing the environmental impact of battery re-X and disposal can be valuable. Standards can guide manufacturers in adopting sustainable manufacturing processes, recycling practices, and reducing the overall environmental footprint of batteries and EVs. Overall, we believe this research has done initial steps toward solving this issue and making attention to the understudied areas.

6.4 Conclusion

The overall aim of the research was to analyze if and how the efficiency and safety of circular battery value chains are supported by existing and upcoming standards that can harmonize and disseminate best practices to facilitate the reuse, remanufacturing, and recycling of batteries. During the research, it has been revealed that such analysis is appropriate for several reasons. First, there is a clear need to identify practical, innovation-related, and regulatory factors that affect remanufacturing. Several of the existing and upcoming standards are intended to support the testing, handling, and specifications of batteries at any life cycle stage. Second, in the context of the circular economy, it is important to understand the bottlenecks and opportunities associated with the use, reuse, and recycling. Third, it is crucial to identify interdependencies and conflicts of interest in the value chain and analyze how they affect the design and administration of battery-based energy storage.

The major gap that was identified with regard to potential challenges throughout the circular battery life cycles is better guidance for benchmarking battery performance using the same specification at all stages of the life cycles. Such guidance needs to be based on non-destructive battery tests. Much still needs to be developed, especially with regard to tests for reused batteries' health and performance and with regard to how to synchronize performance specifications along and across the circular life cycle stages. There is also an urgent need to standardize health tests for safety risks for EV dismantlers and battery logistics. We are aware that such methods are underway, but all steps forward need to promptly be made available as standards. This research has not specifically considered the material recycling of EV batteries, and thus, it would be valuable to conduct future research in this field.

In addition, future research can study the standards and regulations for interoperability EVs and charging stations, since it can enhance compatibility, efficiency, and user experience, promoting seamless integration of EVs into existing infrastructure. Overall, we believe that our study provides a modest heuristic contribution [47] to the literature on EV batteries, which will hopefully attract more researchers to analyze standards and regulations for circular electric vehicle battery lifecycles in the future.

To the best of the authors' knowledge, this study is the first attempt to provide such a comprehensive overview of standards that covers the whole circular electric vehicle battery lifecycles. We believe that the conducted review of standards can play an important role in expanding research knowledge by providing guidelines for the development of sustainable transportation systems and empower researchers to contribute to the enlargement of knowledge and drive innovation in electric vehicle battery research. Continued reviews of international standards will be essential in keeping pace with technological advancements, ensuring safety, and fostering a sustainable transition to electric transportation.

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Chapter 7
Automated 2D-3D-Mapping and Assessment of Defects Obtained from 2D Image Detection on a 3D Model for Efficient Repair of Industrial Turbine Blades

Robert Joost, Stephan Mönchinger, Lukas Engeländer, and Kai Lindow

Abstract Manufacturing processes suited to repair worn-out machine parts are increasingly gaining traction in industrial practice. This evolution is driven by the desire to contribute to sustainable production by extending the lifetime of a part, and methods and machine tools have evolved in the last years, such that the refurbishment reaches equivalent quality compared to new parts. Yet, repair processes often remain too tedious and expensive to be profitable, and are therefore not put in practice. This could be prevented by increased efficiency and automation. In order to repair parts, the defects need to be detected and assessed. This task lies in the field of Reverse Engineering (RE). In the scope of repair and overhaul, RE aims to obtain data and models that can be fed to subsequent applications, such as path planning for additive manufacturing. This paper presents a highly automated process for defect inspection by the example of industrial turbine blades. The current process requires many analogue work steps and human intervention. The developed software processes defects obtained by AI-based image classification. It mainly consists of camera scene calibration, 3D pose estimation, and 2D-3D-mapping. The gained value is the new composition of existing technologies and their customization for turbine blades. Accuracy and computational duration are assessed. The presented method is able to enhance the reparation process and can be deployed to different applications and industries.

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7.1 Introduction

7.1.1 Problem Statement

Due to growing ambitions in sustainability and energy efficiency over the last decade, circular economy concepts are increasingly promoted by policy makers, industry and the scientific community [1]. The so-called retention options for products and materials, also often referred to as R-imperatives, describe efficient ways to improve sustainability. Repair and refurbishment belong to these imperatives—from the sustainability perspective they are more preferable compared to new production. The continuous development of additive manufacturing technologies for the repair of metallic components, such as the direct energy deposition, enhances the establishment of sustainable process chains [2]. However, they always require 3D modeling, either for path planning, selection of the repair process or evaluation of the general repairability. This is where Reverse Engineering techniques [3] are required.

This paper focuses on the repair of worn-out turbine blades of industrial gas turbines. The condition of turbine blades is of particular importance for efficient turbine operation. Blades are exposed to mechanical and thermal strains, causing certain defects and initiating failure mechanisms. Main reasons for failure are mechanical fatigue due to vibration, fretting fatigue, thermomechanical fatigue, creep, corrosion and erosion [4]. Various sources of mechanical vibration as well as high temperature gradients between the outside and the cooled inner surfaces can cause cracks to form and propagate. Likewise, corrosion processes cause base material to be destroyed, when the coating of the blades is removed (spallation). In addition, material can be physically eroded (loss of material), triggered by particles of the destroyed coating. To improve the service life of the blades, they are inspected and repaired after predefined service intervals. Among other things, cracks are removed before they grow too large, the coating is renewed and material is applied if too much base material has been removed by erosion. The basis of the repair process is the detection and assessment of all defects. In the current process, the turbine blades are visually assessed by a worker. The defect locations are labeled manually on 2D views. This information serves as the basis for the decision whether the turbine is suited for repair, as well as for the subsequent machining processes. The repair, although involving lots of manual work, is worthwhile, because high-quality and therefore expensive materials are used. Currently, there are no consistent data and models that ensure a flawless repair process with minimal manual process steps. The highly automated software solution, presented in this paper, alleviates this problem. The software prototype presented automatically transfers defects that are detected on images to a 3D model.

7.1.2 Related Work

The computational tools that will be used are standard tools in the field of computer vision. The main components for the process are (see Sect. 7.2): 3D pose estimation from 2D images, 3D mapping or ray tracing and camera calibration in general.

The goal of pose estimation, often related to object detection and object tracking, is to determine the orientation (rotation and translation) of an object in a real scene, on the basis of at least one 2D image. The template matching method is a commonly used approach [5]. In this scope, the feature-based template matching is applied, since substantial differences are expected in terms of surface structure and orientation between source and target images. This process requires a template, which contains a 2D image with extracted features and their localization on the 3D object to be detected. Having template features and detected features from an actual image that is subject of investigation, a feature matching is carried out. This serves as a basis to approach the so-called Perspective-n-Point (PnP) problem [6]. Respective algorithms require at least three matches to determine translation and rotation coefficients. To deal with outliers and noise and thus gain robustness, RANSAC methods are often included.

Since 2D defects need to be detected on the oriented 3D model, a ray tracing method is required, which corresponds a pixel on the image plane with a specific point on the surface of the 3D model. This requires the projection principle describing the pinhole camera model. Two approaches to this are most common: One way is the classical ray tracing method, where a ray is virtually shot from a pixel on the image plane to check for an intersection with the 3D model surface (e.g., [7]). This can be a computationally expensive task. Spatial hierarchies like kD-trees or Octrees accelerate those methods. The other way is often referred to as projective mapping, where the full 3D model is projected on the image plane in order to find the correspondences between pixel and projected model data and finally calculate the surface parameters of the intersection.

Camera calibration is also required as a basis for the image processing methods. This usually includes camera intrinsic and extrinsic matrices as well as distortion coefficients. Well-documented methods and algorithms are available to determine the camera calibrations, using predefined calibration patterns like checkerboards [8].

7.2 Methods

7.2.1 Existing Framework

Optical Feature Inspection System ("OFIS"). This system is used to capture the images. It consists of a rig with five cameras (Nikon Z5). A customized software serves as control for image capture and cloud storage. In order to cover all outer surfaces of the turbine blade, the camera orientations have been optimized and a

Fig. 7.1 Resulting images, pressure side

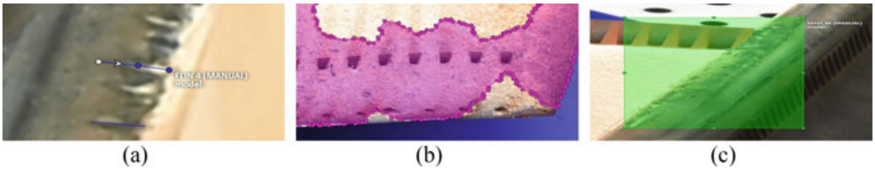

Fig. 7.2 Manual label types for 2D annotations: **a** polyline **b** polygon **c** bounding box

specific procedure to position the blade was developed. There are two poses of the blade: “pressure” and “suction,” referring to the side showing in top direction, and a rough orientation the blade tip has to point to. Each blade yields ten images (2 poses $\times$ 5 cameras); five images of the pressure side are shown in Fig. 7.1.

AI-based 2D Defect Detection. In the scope of the project, an AI-based 2D defect detection was set up. This sub-process is not in the scope of the solution implementation; thus, the technical details as well as key indicators (e.g., accuracy, detection rate) are omitted here. The defects are detected using a YOLOv7 neural network [9]. The training data have been created manually based on the images from the OFIS. There are three types of labels: polyline, polygon and bounding box (Fig. 7.2). The polyline labeling yields in a polygon-type inference; thus, they can be handled the same way as polygons. For each defect type, a suited label is chosen—e.g., polyline for cracks, since they have a rather linear expansion, or polygon for spallations, since these spread rather areal. The resulting image segmentations (“2D annotations”) are present in forms of a COCO file dataset, containing the image data and the 2D annotations as JSON schema.

Software Setup: The developed software is based on the prototype *scangineering* [10, 11], which covers various functionalities and applications regarding the reverse engineering process chain. The software is mainly C++ based and uses different open source libraries.

7.2.2 Requirements and Objectives

First, following objectives and goals of the application have been defined:

- Locating defects on the 3D CAD model
- Assessment of defects in terms of geometric properties like area, length, depth, etc.

- Detection of zone(s) that the defects span.

Regarding the overall concept, following constraints have to be considered:

- OFIS including the camera setup and orientation
- AI-based 2D defect defection with its types of 2D labels (input for the process)
- Original 3D CAD model as BREP STEP model, divided into 14 zones
- Two blade orientations on the OFIS table with unknown exact position.

Having defined objectives and constraints, following features have been identified, that the software must be capable of computing or executing:

- Exact position of the turbine blade on the OFIS table
- Camera calibrations (intrinsics)
- Camera positions (extrinsics)
- Mapping 2D labels from the AI-based 2D defect detection onto the 3D model
- Merging of the mapped 3D defects (one defect may be detected on several images)
- Assessment of mapped 3D defects in terms of geometric properties including determination of affected zones.

7.2.3 The Designed Process Chain

In this section, a brief overview of the designed process is provided, and detailed descriptions follow afterward. The cycle for a single turbine blade is shown in Fig. 7.3. It is divided into pre-process and main process. The pre-process includes camera calibration, OFIS calibration and template generation. The camera calibration consists of intrinsic matrices and distortion coefficients of each camera. In OFIS calibration, the spatial setup of the camera system is determined, including transformation matrices of the cameras (extrinsics). In template generation, a template of the specific turbine blade type is created, consisting of a 3D CAD model, 2D key points and their mapped 3D positions on the model. It serves as object of comparison for the subsequent template matching. The main process starts with the AI-based 2D defect detection, generating images and 2D annotations. Next, the pose estimation determines the 3D position of the turbine blade with respect to the camera system. Afterward, the 2D-3D-mapping is carried out, where the 2D annotations are mapped onto the 3D model and merged afterward in order to obtain 3D defects. In the last step, these defects are assessed and evaluated in terms of spatial and quantitative attributes.

Camera Calibration and OFIS Calibration. For camera calibration, the ChArUco board calibration function provided by OpenCV is used. To this end, a 7 $\times$ 11 board is positioned in various orientations, resulting in 36 images per camera and 180 images total. Next, in OFIS calibration, the aim is to obtain the geometric setup of the camera system. Therefore, a single ChArUco image set is used. Having the 3D coordinate systems of all ArUco markers, the plane of the table is fitted into these points. The virtual table surface is defined as the global x–y-plane and its intersection with the top camera's central axis as origin. The other cameras are oriented by fitting

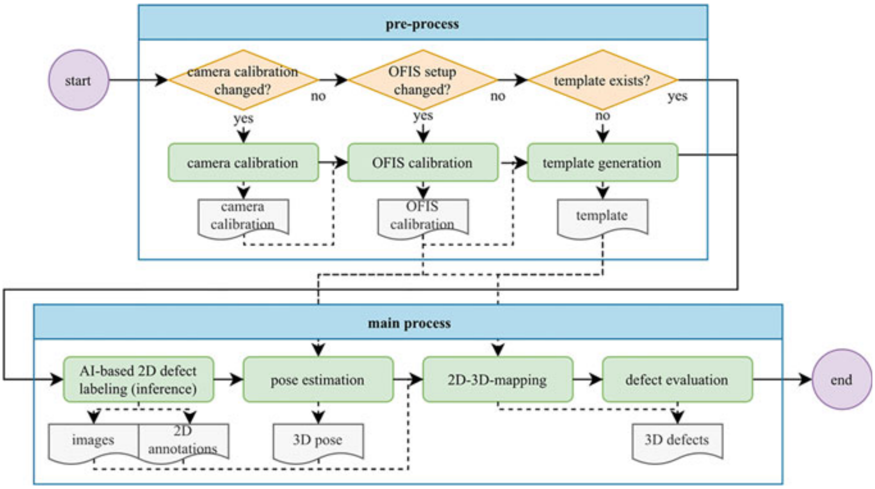

Fig. 7.3 Overall process

the ArUco coordinates using an ICP algorithm. Figure 7.4 shows the actual OFIS (a) and the resulting virtual OFIS calibration (b). The extrinsic coordinate systems are depicted as well as the ChArUco board markers, both connected with rays.

Template Generation. The template generation provides the object of comparison for the subsequent pose estimation and has to be done for each turbine blade type. The input is the OFIS calibration, one reference image set of a turbine blade and the 3D model as triangular meshed surface. The mesh resolution has a significant impact on the computational duration and the accuracy of the results (see Sect. 7.3). With Gaussian blurring applied, the top camera image is used to detect AKAZE descriptors [12]. By manually fitting the 3D turbine blade into the 2D images, an overlay with each camera view is created. Finally, the 2D key points are located on the 3D model by ray tracing. This manual fitting is done for both blade poses. The

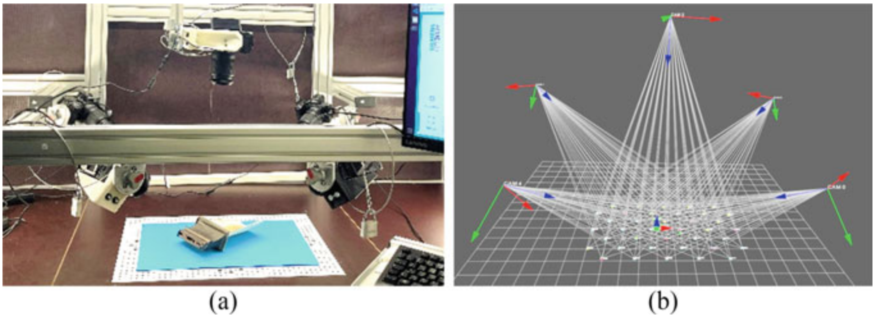

Fig. 7.4 **a** Optical feature inspection system (OFIS) **b** virtual OFIS calibration

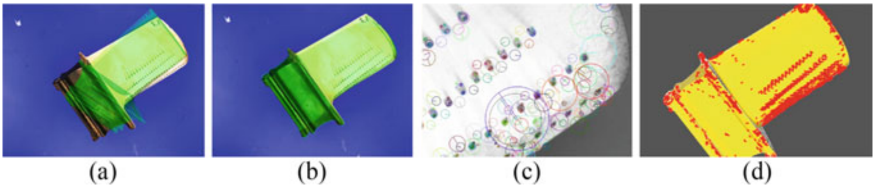

Fig. 7.5 Template generation. **a** not yet fitted overlay **b** manually fitted overlay **c** close-up of detected key points **d** 3D-located key points (red) obtained with ray tracing

template now consists of 2D key points, their 3D locations and a triangular meshed 3D model (see Fig. 7.5).

Pose Estimation. The individual turbine blade assessment starts with the AI-based defect detection. Key points are detected in the top camera image. Next, again using OpenCV's algorithms, a key point matching is run, where correspondences between template and actual blade are found. Using the matched 2D key point coordinates and the 3D coordinates from the template, the resulting PnP-problem is solved. The pose estimation is carried out for both, pressure and suction side. Due to the known OFIS calibration, the orientation of the blade with respect to each camera can be computed.

2D-3D-Mapping. The 2D annotations are now mapped onto the 3D model by ray tracing image pixels in the fully definite 3D scene. All types inherit an area and a boundary; therefore, for each type the inner polygon and a polyline are mapped. A 3D polyline is a vector of 3D points located on the model surface, connected by lines. To obtain the polygon area, all inner pixels could be mapped, but since this would be computationally expensive, a grid mapping method is developed: A pixel grid (every n pixels) is created in 2D, yielding a 3D mapped grid. All polygons underlying this 3D grid represent the inner area. 3D polygons and polylines constitute the so-called 3D annotations. Usually, one defect is detected from several cameras, leading to several 3D annotations that describe the same defect. Therefore, a merging process takes place, that either merges the 3D annotations, or votes, which one is to keep to prevent duplicates. Annotations that are mapped in an acute angle (<45°) are opted out, since smaller inaccuracies arising from OFIS calibration or template generation are amplified.

Defect Evaluation. The defects are finally assessed with regard to quantity and spatial attributes. For each defect, the spanned zones are detected. Depending on the zones, a defect is rated with regard to its severity. For polygons and bounding boxes, the area is of interest, for polylines the overall length. Also, the total number of defects per type are counted for each zone. The quantified defect inspection then serves as a basis to decide if the blade can be repaired or not.

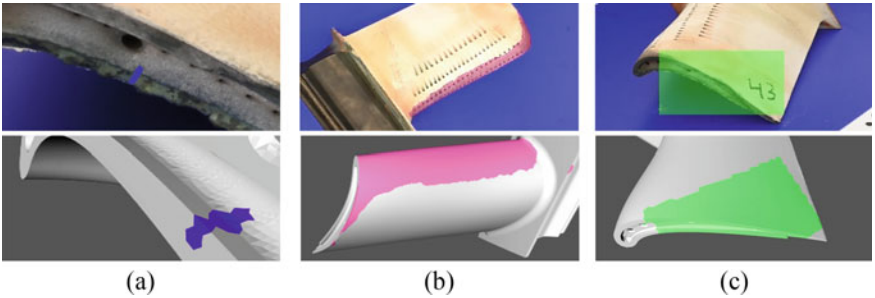

Fig. 7.6 3D defects: **a** crack (polyline) **b** spallation (polygon) **c** material loss (bounding box)

7.3 Results

7.3.1 3D Defects

First, the qualitative characteristics of the 3D defects are presented. Figure 7.6 shows, for polyline, polygon and bounding box, a 2D annotation and the respective 2D-3D-mapping. For all types, the boundary polyline as well as the underlying polygons are stored and affected zones are determined. For polylines, (a) the overall length is measured. The example of a spallation (b) shows that merging of the 3D annotations worked well for the polygon type and the shape is marked precisely. The bounding box annotation type depicts a material loss (c). This type turned out to be only well suited for small defects. For larger defects, since the corners of the bounding box do not necessarily lie on the model surface, the square might not be complete. To compensate this, the inner area of the box is mapped, using the mapping grid similar to the polygon type. The complete 3D bounding box area covers much more than the actual defect; this makes this annotation type for this process rather worthless for large defects (see Sect. 7.4).

7.3.2 Process Refinement and Evaluation

The quantities computational duration, absolute and relative accuracy are assessed. The main adjustable variable is the mesh size of the model. Whereas the absolute accuracy is not substantially dependent on the mesh size, the relative is, since the area of 3D polygons consists of mesh polygons. First, the interplay of mesh size and mapping grid size is assessed. A smaller mesh size requires a decreasing mapping grid size in order to obtain a continuous polygon surface. Figure 7.7a, b show the comparison of a discontinuous and continuous 3D defect. Various mesh and grid sizes and obtained admissible combinations have been tested (Fig. 7.7c). Ideally, the most efficient combinations are used, i.e., 3.0/20, 2.5/20, 2.0/12, 1.5/12, 1.0/8 and

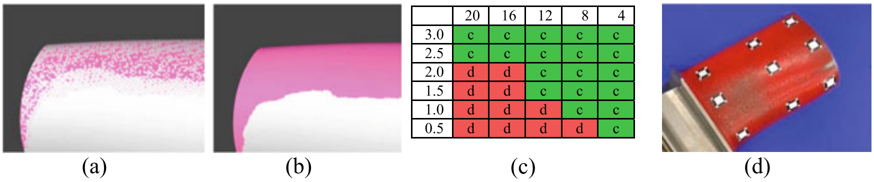

Fig. 7.7 **a** Polygon discontinuity **b** polygon continuity **c** admissible combinations; columns: grid step sizes, rows: mesh sizes [mm]; c = continuous, d = discontinuous **d** 10 × 10 mm^2 markers

0.5/4. Finer step size at given mesh resolution does not affect the result but increase computational cost.

Next, the computational duration in dependence of the mesh size is assessed, using the admissible step/mesh size combinations (Fig. 7.8a). The used turbine blade has typical defects, such as several smaller and larger spallations, loss of materials and cracks. To assess the accuracy, a blade with three center-punched markers (p1–p3), located on the air foil surface, is used. Additionally, 10 mm × 10 mm areal markers are added onto the blade surface and labeled as polygons (Fig. 7.7d). The results are averaged over four different templates and four different blade poses. The absolute accuracy is Euclidean distance between the mapped center-punched markers and their true position, assessed per camera (Fig. 7.8b). Only on cameras 1 and 3, all three center-punched markers are visible. The relative accuracy is defined as the percentual deviation of the mapped marker areas with respect to their true size of 100 mm^2. Not merged 3D annotations (Fig. 7.8c) and merged 3D defects (Fig. 7.8d) are assessed separately.

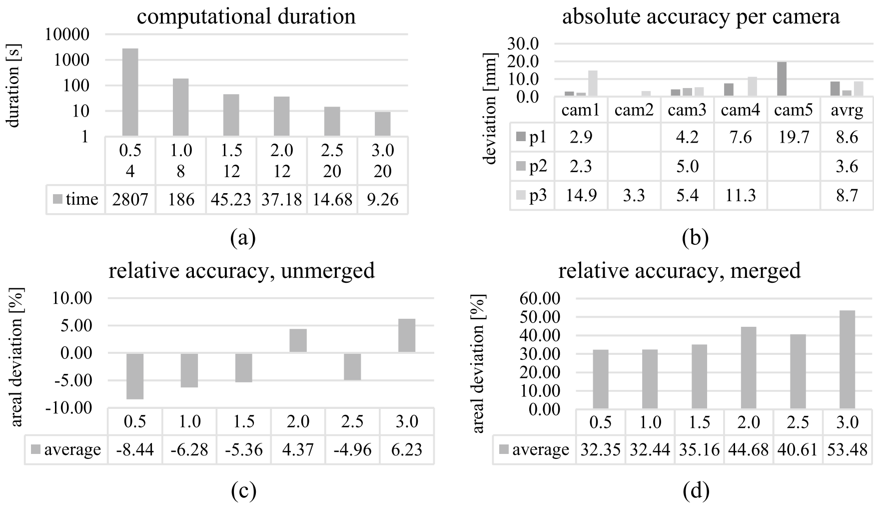

Fig. 7.8 **a** Computational duration for admissible mesh/step sizes **b** absolute accuracy per camera **c** relative accuracy, unmerged 3D annotations **d** relative accuracy, merged 3D defects

7.4 Discussion and Conclusion

The absolute and relative accuracies of the mapping process appear to be sufficient for the evaluation of repairability. The number of defects, the affected zones as well as the approximate spatial extents are known, forming the basis for automated decision. All detected 2D defects are mapped due to sufficient and multiple image coverage of the blade surface. However, the tolerance of several millimeters does not seem satisfactory regarding automated repair. The merged defects exhibit up to 30–60% larger sizes on average, because of 3D annotations that do not coincide, but only overlap. The separate 3D annotations show less than -10% deviation for smaller mesh sizes and average at about 6%. The variability of the absolute accuracy reveals that the OFIS calibration is inaccurate. The camera orientations exhibit slight deviations, leading to amplified inaccuracies during mapping. The error also becomes obvious in template generation, where the overlay fits for cameras 1, 3 and 5, but not entirely for cameras 2 and 4. The reason for this is suspected in the insufficient coverage of calibration patterns. This reveals the need for further experiments regarding camera calibration. Furthermore, the manual fitting during template generation introduces an error, since the overlay is created manually and its accuracy is ensured visually. To improve the precision, a fitting algorithm could be added after the manual process. Regarding the computational duration, 0.5 mm mesh size yields increased time (45 min) compared to 3 min and 0.75 min for 1.0 mm and 1.5 mm, respectively. For industrialization, less than 5 min seems acceptable, in order to outperform manual work. As already mentioned, the bounding box label might not be suited for larger defects. Either, the polygon annotation type could be initially used, or an additional segmentation step after the AI labeling could be executed, in order to extract the exact shape of the defect as polygon. For industrialization, the physical setup would need to be reinforced, since the camera frame moves under contact, falsifying the OFIS calibration.

The developed software provides a complete process chain to locate and assess defects that have been detected on 2D images, on a 3D model. For mapping, a proper error analysis as well as the trade-off between computational duration and required accuracy has been presented. Regardless of the improvable accuracy, the results are already sufficient to decide if the blade can be repaired. Known error sources have been pointed out, leaving optimization for future work. The next logical step is to use the 3D scan model as basis for the mapping, with the aim to represent the real geometry. If larger material losses, spallations or deformations are present, mapping on the CAD model introduces inaccuracies. To obtain the parameterized actual geometry, the scan data would need to be reconstructed. Regarding the complex geometry and having the original CAD model at hand, a CAD morphing approach seems suited. This would enable a variety of automated processes, like detection of difference volumes and automated CAM planning. Furthermore, it remains to apply the technology to other use cases, e.g., molding tools or 3D-printed metallic parts, and assess the transferability.

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Chapter 8
The Environmental Impacts of Cultured Meat Production: A Systematic Literature Review

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Abstract This paper provides an overview of the current state-of-knowledge surrounding the environmental impacts of cultured meat (CM) production. Adopting a systematic literature review (SLR) protocol, over 1,000 papers were retrieved and subsequently appraised through a defined collection of relevance- and quality-based inclusion and exclusion criteria. Utilising Life Cycle Assessment (LCA) literature data, four key LCA impact categories were assessed: land use (crop-eq m^2a/kg); water consumption (L/kg); energy requirements (MJ/kg); and greenhouse gas (GHG) production (kg CO_2-eq/kg). The results indicate that to produce 1 kg of animal meat, CM production systems could require significantly less land, water and energy resources than conventional meat production methods. Major reductions in GHG emissions are also projected, in comparison with conventionally farmed beef. For other meat types, such as pork and chicken, the GHG reduction potential of CM is less substantial and is highly dependent upon the use of renewable energy sources during production. The LCAs reviewed here provide vital insight into the environmental impacts of changing the way we make meat, showcasing what a transition from conventional, to cellular, agriculture could look like for Earth's land, water and climactic systems. The accelerated rate at which the CM industry is expanding and its biotechnological production processes evolving calls for increased LCA study. By periodically reviewing and synthesising the available LCA data in SLRs, the industry and its stakeholders can gather insights into any problematic processes, ingredients or equipment, leading to realisation of optimum environmental efficiency outcomes for producing meat using cellular agriculture technology.

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8.1 Introduction

Over a third of Earth's land surface is currently being utilised for food production [3]. When glacial and barren environments are removed from this calculation, the footprint of global agriculture rises significantly, occupying half of all 'habitable land' available on our planet [9]. Most of this habitable land is used to produce meat, milk and eggs. Comprised of pastureland, grazing areas, and land used to grow animal feed crops, animal agriculture presently occupies an estimated 78% of all agricultural land on Earth [1]. Furthermore, the production of meat, milk and eggs has been identified as a primary cause of global biodiversity loss and a core driver of anthropogenic climate change (ibid.). Humanity's meat consumption habits are therefore responsible for creating two of the Anthropocene's greatest challenges, making the creation of more efficient means of producing animal products critical if we are to sustainably feed Earth's growing population whilst retaining omnivorous diets.

Anthropogenic climate change, the so-called defining crisis of our time [18], necessitates attention from governments, academics, industries and consumers in the search for solutions to mitigate (and potentially reverse) global warming. Increased awareness of animal agriculture's 'foodprint', a concept defining the overall environmental impacts generated by particular foods [5], has highlighted the benefits of a widespread transition towards meat-free or meat-reduced diets. Whilst the number of consumers adopting climate-friendly diets, for instance, veganism, vegetarianism, flexitarianism and climatarianism, has risen significantly over the past decade [2], humanity as a whole remains reluctant to remove animal products from our diets. This has necessitated the creation of innovative technologies capable of meeting the demand for meat whilst also mitigating its catastrophic impacts on Earth's natural environment. One such technology is cellular agriculture.

Cellular agriculture applies a range of principles, processes and equipment to produce animal products from cell cultures. The industry is currently focused on animal products, creating meat, eggs and milk products, without the subsequent environmental, social and ethical issues that are sometimes associated with rearing and slaughtering livestock. One of such products is cultured meat (CM), which is lab-grown meat.

Nevertheless, the consideration of scaling up of CM production is mostly confined to developed countries, where the legislation from governments is under development, e.g., the U.S. Food and Drugs Administration [19], the Food Standards Authority (FSA) in the UK [14] and the Food Standards Australia and New Zealand [4].

The environmental impacts associated with replacing conventional animal agriculture with cellular agriculture can be measured through the Life Cycle Assessment (LCA) method. LCA can be used to quantify the ecological impacts of a product over its full life cycle, generally including raw material extraction, processing, manufacturing, distribution and use [10]. The most common system boundaries used within LCA are 'cradle-to-gate', 'cradle-to grave', 'gate-to-gate' and 'cradle-to-cradle'.

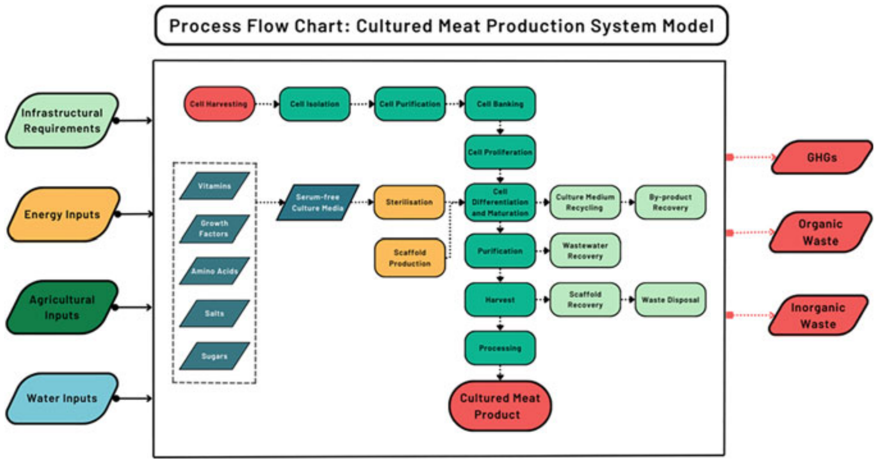

Fig. 8.1 Process flow chart: cultured meat production system model

Figure 8.1 shows our depiction of a potential CM production system. It shows the components and processes of the CM production process that exist within a cradle-to-gate system boundary. As there are multiple cellular agriculture companies, working on a diverse range of CM products, with laboratories and production facilities dispersed across multiple geographical regions, this production process is anticipatory and may not be inclusive of all necessary inputs and stages. Additionally, the LCA methodology provides scope for studies to design completely unique system boundaries, which may exclude certain aspects of the production process entirely, creating further uncertainty.

The remainder of this paper is organised as follows. Section 8.2 shows the SLR steps followed in this research. Section 8.3 presents the key findings. Section 8.4 discusses the key results considering recent literature. Section 8.5 provides some conclusions, limitations and further research avenues.

8.2 Systematic Literature Review (SLR)

Through conducting a SLR of this field, the aim of this research is to provide a synthesis of the current state of knowledge on the environmental impacts of CM production and highlight gaps for future research.

8.2.1 *Search Strategy*

The search for CM research was performed in March 2023 and limited to literature published post-2010. Searching the database Scopus using the following search string: 'TITLE-ABS-KEY ("cultured meat" OR "cultivated meat" OR "lab-grown meat")', highlights an increase from 2 to 212 in CM-related publications from 2010 to 2022.

For the SLR, five databases were utilised in the search: Scopus, Web of Science, ProQuest, Google Scholar and Science Direct. Research specifically focused on CM remains limited in most disciplines at present; however, the field is expanding rapidly. A total of 9253 CM-related publications were found that mention CM in some form. Most results, 7160 of 9253, were found on Google Scholar which did not have search refinement functionalities as advanced as the other databases utilised here. Subsequently, the Google Scholar search engine uncovered a substantial volume of research of low relevance to CM, including articles that only briefly or passively mention CM within text (i.e., general food sustainability articles), and also results from non-academic sources, including news articles, editorials and blog posts. As this research solely concerns the LCA studies conducted on CM, the additional terms 'Life Cycle Assessment' and 'LCA' were added to the search string in each database to further refine the results. Refreshing the search strategy to target only the CM publications that meet the additional criteria of mentioning the LCA method within their title, abstract, keywords or main text reduced the literature pool to 2,093 results across all databases. See Fig. 8.2.

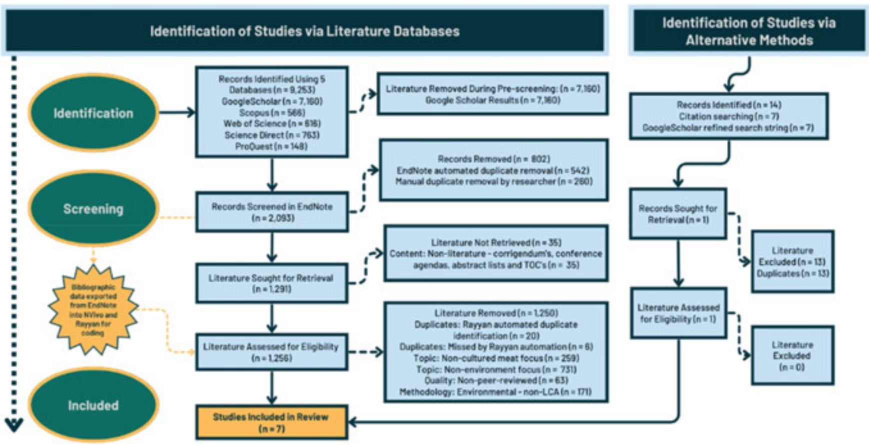

Fig. 8.2 Search strategy used in Systematic Literature Review of cultured meat (2010–2023)

Table 8.1 Systematic literature review inclusion and exclusion criteria

	Inclusion criteria	Exclusion criteria
Literature type	Journal articles, book chapters, high quality grey and white literature	Magazines, newspapers, industry reports, poor quality grey and white literature
Date range	Post: 1st January 2010 Pre: 10th March 2023 (Present)	Pre: 1st January 2010 Post: 10th Mar-2023 (Present)
Content	LCAs of cultured meat	Non- LCA, non-cultured meat, review papers
Quality	Peer-reviewed, methodologically sound, scientifically credible	Non-peer-reviewed, methodologically flawed, low scientific credibility
Language	English	Non-English (unless translatable)

8.2.2 Appraisal

The appraisal phase consisted of two primary steps. Firstly, refining the literature based on relevance to the research questions, and secondly, assessing the quality, credibility, methodological rigour and overall soundness of the relevant research. Results were input into the reference managing software EndNote to undergo this screening. After duplicates were removed, the abstracts of the remaining literature were analysed to determine their relevance to this study.

Literature that did not focus on the environmental impacts of CM was outside of the scope of this research and therefore excluded. Furthermore, literature that explored the environmental dimensions of CM but did not employ the LCA methodology was also excluded and, however, were kept for consultation and for contextual knowledge and additional insight. The inclusion criteria papers were assessed against for acceptance into final review are listed in Table 8.1.

In total, eight LCAs of CM were identified through this SLR process and one additional study [17] was discovered through backward and forward searching. To ensure all published LCAs of CM had been discovered through this SLR's methodological approach, the titles and authors of the eight papers were input into Litmaps online software to search for connected papers. No new results were found through Litmaps, confirming the robustness of this SLR's search strategy. The papers selected for full review are listed in Fig. 8.5. Seven of the eight CM LCAs were determined to have met the set inclusion criteria. The LCA conducted by [7] could not be included due to its focus on a plant-based CM hybrid product, with CM comprising only 16.9% of its total mass.

8.2.3 Synthesis

The synthesis stage consisted of identifying, extracting and categorising the relevant data contained within the literature selected for inclusion. This data was selected and

Fig. 8.3 Criteria for information extraction

subsequently recorded in individual data collection sheets. The data synthesis sheet utilised here included sixteen criteria for information extraction, shown in Fig. 8.3.

Employing SLR analysis and reporting, whereby each paper was assessed through an identical procedure, aided in reducing the potential for reviewer bias whilst also ensuring the development of a holistic and complete account of the literature field. This approach required the extraction of certain textual content of the included studies, for instance the LCA results, but also went beyond this to include the contextual, non-research dimensions of the publications, such as where and by who, CM LCA research is being published (institutions, author's countries, journals, etc.). Mapping the research landscape in this manner proved useful in identifying key research gaps and understudied topics within the literature, and the journals, institutions and researchers dominating this research field.

The data extraction sheets were uploaded to NVivo, along with a pdf of each full article, for content coding. NVivo software is typically utilised for qualitative data analysis but proved useful in this SLR as it allowed for the coding and visualisation of numerous quantitative and qualitative features within the included papers. Utilising the data visualisation features available on NVivo, maps of convergent and divergent factors between papers were generated which assisted with the identification of themes, for instance, which papers utilised a certain LCIA method (e.g., ReCiPe) and which papers analysed or excluded certain impact categories (e.g., which and how many papers included water usage in the assessment). After completing this process, the synthesised information was used for the SLR report write-up.

8.3 Findings

8.3.1 Cultured Meat (CM) Literature Landscape

Figure 8.4 shows the distribution of CM literature on Scopus, segregated by research discipline and published from 2010 onwards. 7.1% ($N = 87$) of all research literature on CM between this date range has been categorised as Environmental Science.

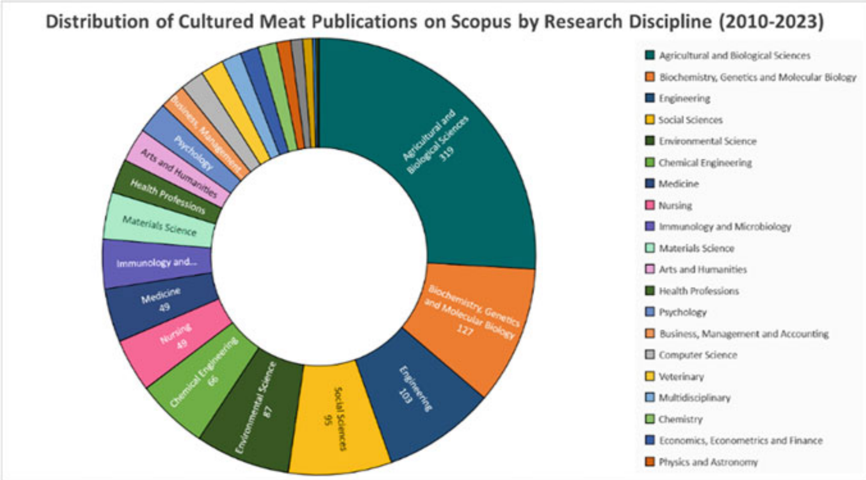

Fig. 8.4 Distribution of cultured meat publications on Scopus by research discipline (2010–23)

8.3.2 Life Cycle Analysis (LCA) Studies of Culture Meat Production

Figure 8.5 presents the LCA results of the seven studies reviewed. The only conventional meat product [13] assessed CM against was poultry where they found CM to produce approximately five times more GHGs. Mattick et al. [8] calculated that commercial-scale CM production would produce less GHGs than beef production but double than those emitted for the same FU of conventional pork and triple the emissions of poultry. Sinke et al. [11], however, calculated the carbon footprint of CM to be significantly lower than all forms of conventional meat production when sustainable energy is used during its production. If conventional energy is utilised within the CM facility, the meat produced has a lower GWP than beef but a slightly higher GWP than pork and poultry meat production. Whilst all studies agree that CM is likely to require less land than conventional meat production, discrepancies arise when comparing the Global Warming Potential (GWP) of CM calculated by each study. Tuomisto et al. [16] reported GHG emissions for CM significantly lower than those from conventional beef, sheep, pork and poultry meat production, whilst Tuomisto et al. [17] reported GHG emissions that remain significantly lower than those recorded for conventionally produced beef, sheep and pork, but are higher than those for poultry.

Study	Cell Culture Medium	Functional Unit (FU)	Key Findings (per kg)
Sinke, Swartz, Sanctorum, van der Giesen (2023)	Glucose, Soy Hydrolysate, Amino Acids from Microbial and Chemical Production, Microbial Recombinant Protein Production	1kg cultured meat product from land based animal with 20-30% dry matter content and 18-25% protein content	2.21-24.8 kg CO_2-eq/kg 116.48-481.70 MJ/kg 2.25-3.59 m2a crop-eq/kg 60-150 L/kg
Tuomisto, Allan and Ellis (2022)	DMEM and FBS (CMB and CMB128 scenarios) Essential 8™ (serum-free medium scenarios, CMC, SFB & SFE)	1kg cultured meat product consisting of skeletal muscle cells with 30% dry matter content and 20% protein content	4.88-25.19 kg CO_2-eq/kg 94.09-532.78 MJ/kg 1.84-6.89 m2a crop-eq/kg 120-540 L/kg
Sinke and Odegard (2021)	Soy Hydrolysate, Glucose from Maize	1kg high-protein cultured meat product	2.5-13.6 kg CO_2-eq/kg 147-264 MJ/kg 1.7-1.8 m2a crop-eq/kg 42-56 L/kg
Mattick, Landis, Allenby and Genovese (2015)	Soy Hydrolysate, Glucose, Glutamine	1kg cultured meat product	3.15-22.28 kg CO_2-eq/kg 43.46-315.8 MJ/kg 2.92-8.47 m2a crop-eq/kg
Smetana, Mathys, Knoch and Heinz (2015)	Cyanobacteria Hydrolysate	1kg ready-to-eat product on consumers plate 3.75 MJ energy content of ready-to-eat product on consumers plate0.3 kg of digested proteins supplied to consumer	23.9-24.64 kg CO_2-eq/kg 290.7-373 MJ/kg 0.39-0.77 m2a crop-eq/kg
Tuomisto, Ellis and Haastrup (2014)	Cyanobacteria Hydrolysate, Wheat, Corn	1000kg ground cultured meat product with 30% dry matter content and 19% protein content	2.3-3.4 kg CO_2-eq/kg 38.7-60.9 MJ/kg 0.46 m2a crop-eq/kg 516.4 L/kg
Tuomisto and Teixeira de Mattos (2011)	Cyanobacteria Hydrolysate	1000kg ground cultured meat product with 30% dry matter content and 19% protein content	1.9-2.2 kg CO_2-eq/kg 26-33 MJ/kg 0.19-0.23 m2a crop-eq/kg 367-521 L/kg

Fig. 8.5 Cultured meat life cycle assessments (2010–2023)

8.4 Discussion

Systematically reviewing the CM literature landscape has highlighted significant knowledge gaps in our understanding of the environmental dimensions of this emerging biotechnology. Only eight LCA studies of CM were found in the existing literature. This deficit in environmental research also exists outside the confines of LCA research, with CM literature that focuses primarily on its environmental dimensions being rare. Considering the catastrophic environmental implications of present global meat production practices, the environmental potential of a transition towards CM is often a central feature of its public, media and industry discourse. However, environmental research constituted less than 10% of all CM literature published between 2010 and 2023. Within this <10%, the primary focus is predominantly on anthropocentric features of CM and the environment. For instance, emerging from the fields of psychology, philosophy, sociology and various other social sciences, discourse analyses and consumer acceptance studies comprise over half of all literature identified in this SLR as having any substantial level of environmental focus. Most of these studies feature the environment as a small subsection within their wider research, e.g., identifying potential environmental benefits as one of many factors influencing consumer acceptance. Focusing on human cognition and our socio-politico-economic systems, the environmental literature on CM primarily examines how we conceptualise it, what we think about its environmental impacts and where, or more specifically, if, it has a place in our diets within a climate changing world.

As is evident from the analysis of the literature, there is high variability within the results of the available CM LCA studies. This variability arises because of each study utilising a range of different system boundaries, LCI databases, LCIA methods and methodologies, and the inclusion of different system inputs and processes. The studies reviewed here adopted a wide variety of different approaches and therefore produced vastly different results. They also focused on different environmental impacts, with some studies choosing to omit water requirements, i.e., Mattick et al. [8] and others choosing to include data on aspects such as particulate matter formulation [11]. As the CM industry continues to expand and improve the systems, technologies and methods utilised in CM production, the accuracy of system-based information is increasing, and the anticipatory or hypothesised nature of CM's environmental impacts is becoming less uncertain. This is evident within the development of CM LCAs since the first published LCA study.

8.5 Conclusions, Limitations and Future Research

This SLR adds to the growing body of environment-focused CM literature by providing a systematic and comprehensive assessment of the available LCA studies and their quantitative environmental impact assessment data.

There is a growing interest in the current literature about the potential of CM, especially in developed countries. The legal and environmental regulations from government would need to be considered if CM is to become mainstream. There is a potential that CM can help reduce GHG emissions substantially, therefore contributing to the amelioration of climate change negative impact.

LCA is grounded in systems thinking. However, one of its limitations is that it is not a method that can be utilised to provide generalised data on the environmental impacts of a certain product on a national or global scale, as the systems in which the product is made can differ significantly. For instance, the production of 1 kg of beef from a Concentrated Animal Feeding Operation (CAFO) situated in an arid region of the USA will have significantly different environmental impacts to those of the production of 1 kg of beef from pasture-raised cattle in the temperate UK climate. As is evident, a single LCA of beef production cannot be used to determine the environmental impacts of beef production on a global scale because the results will be context specific and may only be applicable only to the studied system and the product it creates.

Future research avenues include that LCAs should focus on ensuring a comprehensive system boundary that is inclusive of all relevant inputs during the production cycle. Adopting the approach outlined in [13] of including multiple FUs, this future LCA will avoid focusing on a singular mass-based FU at the expense of nutritional values. Further to this, multiple methods, e.g., [6], should be employed to identify the sensitivity of the results obtained during the initial study. Using the most recent industry data for the life cycle inventory inputs, adopting multiple life cycle impact assessment methods, assessing both mass and nutrition based functional units, and situating the hypothesised commercial-scale CM production system within specific geographical locations will enable the elaboration of more comprehensive CM LCAs in future.

In summary, the following open issues have been identified in this paper; in the context of CM and LCA, there is a need for more research on:

- CM in the Environmental Sciences,
- Standardisation of LCAs methods,
- Agreement on the types of environmental impacts to consider,
- Inclusion of consumer perception data and
- Legislation by governments to regulate scaling up of CM production.

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Chapter 9
Finite Element Analysis of the Mechanical Properties of Laser Powder Bed Fusion-Produced Ti6Al4V Sheet- and Skeleton-Gyroid Structures

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Abstract Triply periodic minimal surface structures manufactured by additive manufacturing are one of the most important means to achieve lightweight in various fields. However, their manufacture using laser powder bed fusion still requires considerable research. In this study, three gyroid structures with volume fraction ranging from 10 to 30% were designed and fabricated using Ti6Al4V. Their mechanical properties, failure modes and energy absorption properties were studied by simulation prediction and experimental test. The results show that their elastic modulus, yield strength, peak stress and the energy absorption enhance with the increase in the volume fraction. The simulation results are in good agreement with the experimental results. Two failure modes appear on the adjacent side of the structure, namely 45-degree shear failure and layer-by-layer unit brittle collapse. In terms of energy absorption, the energy absorption efficiency of large volume fraction structure is more stable. This study significantly enhanced the understanding of gyroid structure and provided a more reliable basis for the selection of TPMS structure types and design parameters.

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9.1 Introduction

In recent years, laser powder bed fusion (L-PBF) has become the preferred technology for additive manufacturing (AM) due to its ability to produce high-strength and less-defective metal components [1]. L-PBF can be used to fabricate stable and lightweight lattice structures, including complex triply periodic minimal surface (TPMS) lattice structures that cannot be produced using conventional manufacturing methods, by using a laser energy source to melt metal powders through layer-by-layer scanning [2]. TPMS structures are topologically ordered three-dimensional, porous structures composed of one or more repeating unit cells defined using mathematical concepts [3] such as the Schoen Gyroid, the Schwartz diamond and the Neovius. The mechanical properties of these TPMS lattice structures could be controlled by tuning various parameters, such as thickness, rod diameter, volume fraction and porosity [4], which is why TPMS lattice structures have great commercial utility, are widely studied and have applications in many fields, especially for the designing of lightweight bio-bone implants [6] and aerospace components [7].

In the previous studies, the relationship between the mechanical and the geometric properties of TPMS lattice structures under different loading conditions (such as compression [8], impact [9] and fatigue [10]) has been examined using various methods (such as theoretical derivation [11], finite element analysis (FEA) [12] and sample tests [13]). Maskery et al. [14] studied the effects of unit size on failure modes and energy absorption by designing five gyroid structures with different unit sizes with 22% volume fraction through compression experiments, and found that samples with larger cell sizes showed local fracture, while samples with smaller cell sizes resulted in diagonal shear failure. Ma et al. [15] compared the morphology and mechanical properties of five groups of sheet and strut structures with different porosities through compression tests, and the results show that compared with strut structures, sheet structures have greater elastic modulus, energy absorption and better repeatability. Bonatti et al. [16] performed finite element simulations for more than 800 varying sheet lattices with relative densities ranging from 1 to 80%, and found shell lattices have substantial advantages over truss lattices with respect to strength, stiffness and energy absorption properties. Zhao et al. [17] systematically studied the mechanical properties, deformation behaviors and energy absorption properties of constant density sheet structure and functionally gradient sheet structure by compression test and finite element method. The results showed that the energy absorption of functionally gradient structure was higher than that of uniform structure.

Despite the aforementioned research, TPMS lattice sample tests are usually unitized to evaluate the mechanical behavior of these structures, while little attention has been paid to the FEA approaches for predicting the failure behavior of strut-based TPMS structures. In the case of specific unit size requirements, such as in scaffold design [18], it is important to investigate and select the appropriate volume fraction to ensure that it does not affect the failure mode. Therefore, in this study, in order to reduce the high manufacturing cost of L-PBF samples and reduce the number of time-consuming mechanical tests, the FEA approach based on the Johnson–Cook damage model was used to predict the mechanical properties and failure behavior of three gyroid structures with volume fraction ranging from 10 to 30%. And compression tests were also conducted to illustrate the feasibility of the proposed FEA approach.

9.2 Methodology

In this section, we present the design method and the fabrication of the gyroid structure (GS). All the samples were designed and fabricated using L-PBF. The GS structures were then tested by compression experiments and simulated by using finite element analysis (FEA) with ABAQUS.

9.2.1 Design of Gyroid Structures

As a typical TPMS lattice structure with excellent comprehensive performance, the gyroid lattice can improve the mechanical properties by adjusting the parameters and also achieve lightweight.

Gyroid lattice structure is designed by the following implicit function:

$$\varphi_{\mathrm{GS}}(x, y, z) = \cos(x) \bullet \sin(y) + \cos(y) \bullet \sin(z) + \cos(z) \bullet \sin(x) - t = 0 (1)$$

where t is the offset parameter that controls the volume fraction (V_f), and it changes its shape by unidirectional offset isosurface in the method shown in Fig. 9.1a and then solidifies one of the regions to form a unit. Finally, the target structure is obtained by array. As shown in Fig. 9.1b, three kinds of GS structures with volume fractions of 10%, 20% and 30% are designed according to the fitting linear relation between V_f and t. Each structure is a $6 \times 6 \times 6$ cube arrayed by a 3 mm-long unit along a three-dimensional coordinate axis.

9.2.2 Materials and Fabrication by L-PBF

The structures use Ti6Al4V powder (Ti ~ Allowance, Al ~ 6.78, V ~ 4.32, O ~ 0.16, Fe ~ 0.07, TLS Technik Gmbh, Germany) as the material. As shown in Fig. 9.2, the samples were manufactured by using SLM 280 2.0 machine (SLM Solutions, Germany), with argon as protective gas, at 1100 mm/s laser speed, 275 W laser power, 80 μm spot diameter and 30 μm layer thickness. These samples were named GS10, GS20 and GS30 according to their volume fractions.

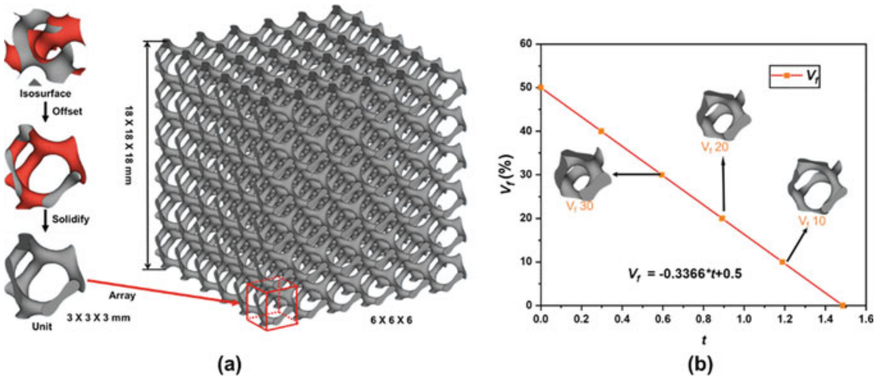

Fig. 9.1 **a** Modeling process of GS and **b** relationship between the volume fraction V_f and offset parameter t for GS

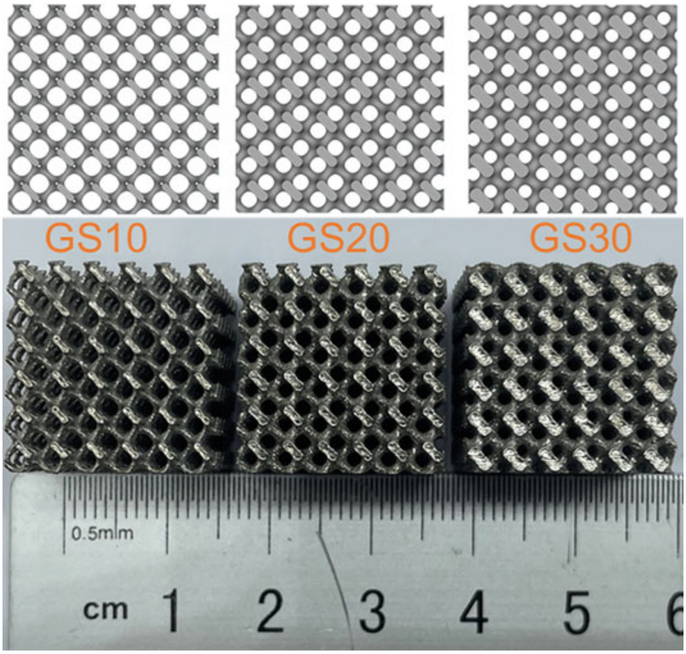

Fig. 9.2 Ti6Al4V GS manufactured by L-PBF

9.2.3 Compression Experiments

According to the standard of Compression Test for Porous and Cellular Metals (ISO 13314:2011), compression tests were carried out to investigate the mechanical properties and observe the destruction processes of compression by using a universal test machine (WAW-600, SUNS, Shanghai) with a 300 KN load cell for these GS structures.

All samples were placed between the two plates, and the upper crosshead was loaded downward along the z-axis at a speed of 2 mm / s, and the strain above 0.5 was compressed, and the compression process was recorded by the camera. The stress–strain diagram can be calculated from the force–displacement data, and then, the elastic modulus (E), yield strength (σ_p), peak stress ($\sigma_{\max}$) and energy absorption (EA) can be obtained.

9.2.4 Finite Element Analysis

In order to clearly describe the stress concentration and failure deformation behavior during compression, the finite element analysis (FEA) of gyroid structures was conducted with the commercial FE package Abaqus/Explicit 2021.

As shown in Fig. 9.3, the GS models were placed between two rigid parallel plates meshed with quadrilateral elements (R3D4), the bottom plate remains stationary, and the top plate moves downward to compact the sample by 50%. In order to simulate the boundary conditions in the compression process, a friction coefficient of 0.2 is set between the rigid plate and the model. Then, GS models were meshed with tetrahedral elements (C3D4) and the average element size was 0.2 mm according to the meshing strategy of Yang et al. [19].

In addition, the material properties were set with according to previous studies [20] with a density of 4.43 g/cm3, Young's modulus of 108090 MPa, Poisson's ratio of 0.3 and plastic parameters (in Table 9.1). In order to simulate the damage of materials during compression, the Johnson–Cook damage model was set up in the material properties. The Johnson–Cook damage model can be described as following formula:

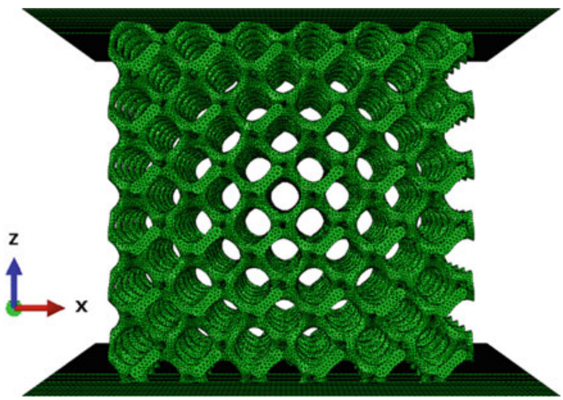

Fig. 9.3 Representation of C3D4 mesh models generated for finite element analysis of GS

Table 9.1 True plastic stress and strain of Ti6Al4V

Yield stress(MPa)	1189	1229	1253	1268	1282	1289	1294	1296
Plastic strain	0	0.002	0.004	0.006	0.009	0.012	0.016	0.02

$$\varepsilon_f = \left[D_1 + D_2 \cdot \exp\left(D_3\sigma^*\right)\right] \cdot \left[1 + D_4 \ln\left(\dot{\varepsilon}^*_{\text{eq}}\right)\right] \cdot \left[1 - D_5 T^*\right] \tag{9.2}$$

where the D_1, D_2, D_3, D_4 and D_5 are the material damage parameters, and σ^* is the stress triaxiality. $\dot{\varepsilon}^*_{\text{eq}}$ is the plastic strain rate of dimensionless equivalent and the T^* is the dimensionless temperature. Referring to the research of Zhao et al. [17], D_1, D_2 and D_3 were set to 0.005, 0.43 and −0.48, respectively, while D_4 and D_5 are not considered.

9.3 Results and Discussion

In this chapter, the mechanical properties of GS structure are reported and the failure modes are analyzed by compression test and simulation.

9.3.1 Elastoplastic Properties

The mechanical properties were determined for GS10, GS20 and GS30, covering three sets of repeated experiments for each one. The stress–strain curves of GS10 shown in Fig. 9.4 are calculated according to the force–displacement curve obtained in compression test and simulation. The stage before the first wave peak of the curve is the elastic stage that can be fitted to a straight line, and its slope represents the elastic modulus (E) of the structure. The fitted straight line is shifted to the right by 0.2% and intersected with the curve, and the stress at the intersection point is the yield strength (σ_p). And the stress value of the first peak of the curve is the peak stress ($\sigma_{\max}$). In these curves, it can be seen that the three sets of experimental curves have great repeatability, which indicates that the samples manufactured by L-PBF have good structural and mechanical property consistency. By comparing the data results of simulation and experiment, they have similar curves, which experience linear growth, stress drop and stress plateau. The peaks between FEA and GS10 are a little different, this is because the simulated model is ideal, there are manufacturing errors compared with the as-built samples, and far less complex than the real situation of the sample under actual working condition. Nevertheless, this difference does not affect the simulation results to truly reproduce the mechanical properties of the GS structure.

As shown in Table 9.2, the mechanical properties of each structure sample are calculated and counted in the form of mean ± standard deviation. It can be seen from

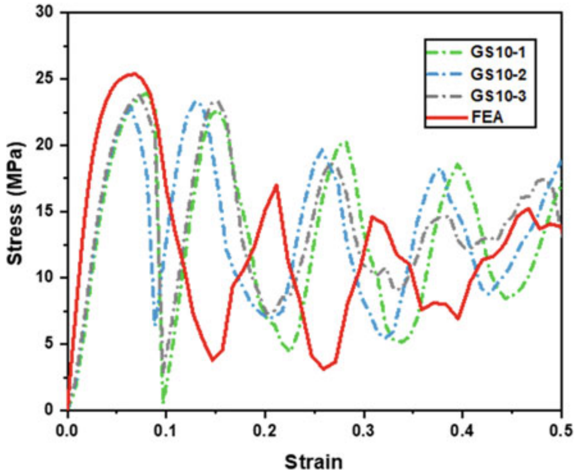

Fig. 9.4 Stress–strain curves of the GS10

Table 9.2 Mechanical properties of GS structure

Type	Elastic modulus (MPa)		Yield strength (MPa)		Peak stress (MPa)	
	EXP	FEA	EXP	FEA	EXP	FEA
GS10	542.5 ± 3.8	787.9	18.0 ± 0.3	19.4	23.8 ± 0.2	25.4
	Δ = 45.2%		Δ = 7.8%		Δ = 6.7%	
GS20	1453.9 ± 243	2266.4	61.9 ± 1.3	65.4	77.9 ± 0.2	75.4
	Δ = 55.9%		Δ = 5.7%		Δ = -3.2%	
GS30	3088.8 ± 89.1	4805.7	115.2 ± 6.4	122.3	143.9 ± 2.5	140.4
	Δ = 55.6%		Δ = 6.2%		Δ = -2.4%	

this table that the GS structure with larger volume fraction has larger E, σ_p and $\sigma_{\max}$. It's worth noting that the standard deviation of the GS structure with small volume fraction is smaller, which indicates that the stability of the mechanical properties is better. The error of the elastic modulus of all samples is stable at about 50%. This is because the uneven upper and lower surfaces of the samples after wire cutting lead to the experimental elastic modulus being less than the FEA value [17]. It is observed that the FEA results except elastic modulus are very close to the experimental values, which indicates that the simulation parameters are set reasonably and have high confidence performance prediction.

9.3.2 Deformation Behavior

The deformation process of each sample was recorded, and the failure characteristics of each sample were analyzed by combining experiment and simulation. In general,

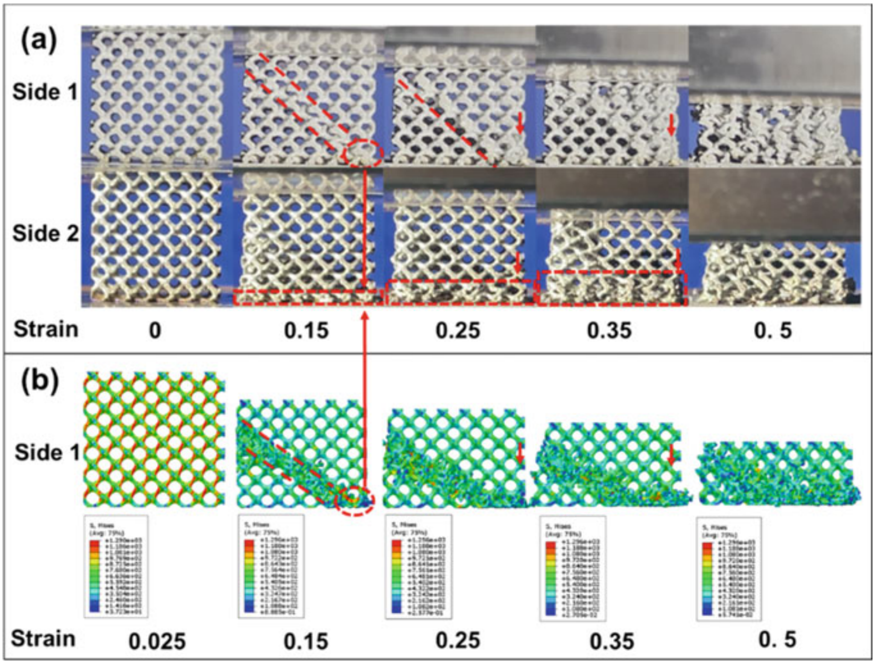

Fig. 9.5 Experimental and simulated failure modes of GS10

the failure behavior of the simulation was very similar to that of the experiment. In GS10, GS20 and GS30, 45-degree line shear and unit brittle fracturing occurred. As shown in Fig. 9.5, the failure process of GS10 is analyzed, where side 1 and side 2 are adjacent. When the strain is 0.025, the GS structure was in the elastic stage, and the stress was mainly concentrated at the connection of the struts (see Fig. 9.5b). Therefore, the connection of these struts first broke with the increase of strain. When the strain is 0.15, 45° shear failure occurred at side 1 of GS10, and the unit brittle collapse at the bottom marked with a circle corresponds to side 2. With the increase of strain, the structure slipped along the shear band in side 1 and collapsed layer by layer at the bottom of side 2. Each collapse of the structure corresponds to a decline in the stress–strain curve, and then, each layer of the structure is compressed and densified, which corresponds to the rise of the curve.

9.3.3 Energy Absorption Characteristics

The area between the stress–strain curve and the X-axis is defined as energy absorption (EA). The EA of G10, G20 and G30 under experiment and simulation is shown in Fig. 9.6a, and the EA increases with the increase of volume fraction. It can be

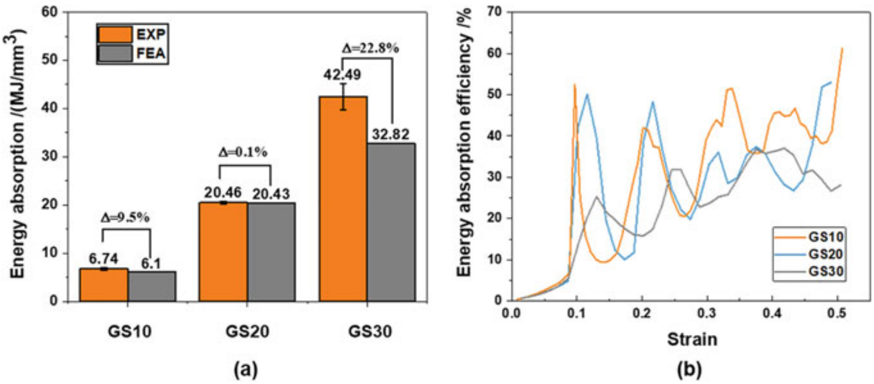

Fig. 9.6 **a** Energy absorption and **b** energy absorption efficiency of GS

seen from the error bar in the figure that the structure with smaller volume fraction has more stable energy absorption performance.

The energy absorption efficiency (EAE) with strain changes is shown in Fig. 9.6 (b). It can be clearly observed that the EAE curve of GS10 fluctuates most violently, while that of GS30 is the gentlest. Moreover, the strain at the first curve fluctuation decreases with the decrease of the volume fraction. These phenomena are because the structure with a smaller volume fraction is more prone to instability under load, resulting in a sharp change in energy absorption efficiency.

9.4 Conclusions

In this paper, the mechanical properties and failure behavior of Ti6Al4V gyroid structures with three volume fractions, ranging from 10 to 30%, fabricated by laser powder bed fusion under compressive load were studied by experiments and simulations. The main conclusions of these results are as follows:

(1) The mechanical properties of G structure have high stability and repeatability. The elastic modulus, yield strength and peak stress of the structure ranged from 542.5 ± 3.8 to 3088.8 ± 89.1 MPa, 18.0 ± 0.3 to 115.2 ± 6.4 MPa and from 23.8 ± 0.2 to 143.9 ± 2.5 MPa, respectively. The GS30 has the highest E, σ_p and $\sigma_{\max}$, which means that it can better resist failure deformation under the same load.
(2) The simulation using Johnson–Cook model is in good agreement with the experimental test, revealing the mechanical response and deformation behavior of the gyroid structure under compressive load. The failure behavior of the three GS structures is similar, with 45-degree shear failure and layer-by-layer unit brittle collapse.

(3) The energy absorption of the structure ranged from 6.74 ± 0.27 to 42.49 ± 2.71 mJ/mm^3. As the volume fraction increases, the energy absorption increases and the energy absorption efficiency is more stable. This is because the structure with a smaller volume fraction is more prone to instability under load, resulting in a sharp change in energy absorption efficiency.

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Chapter 10
The Gamification of Circular Practices Using the SDGs

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Abstract Global society is increasingly committed to facilitating responsible business practices and long-term value creation in developing more sustainable economic growth which is demonstrated within the global sustainable development goals (SDGs). Gamification provides an opportunity to increase sustainable awareness and behaviours by providing instantaneous rewards for completing desired pro-environmental tasks. These actions are based on circular economy practices, seeking to keep waste minimal, extending and closing the loop. A case study methodology was used to examine the gamified sustainability scheme launched by a higher education institution in the United Kingdom. The examined project covered four categorisations of sustainability games and apps, as well as optimising key gamification principles of realistic goals, clear progression and rewards, as well as using strategy and novelty to engage users. Furthermore, the project examined the delivery of five of the seventeen SDGs and four of the circular practices. Demonstrating that although gamification principles had been utilised to encourage circular practices in this case, further consideration should be given to the remaining SDGs and circular principles to ensure a balanced approach to sustainable operations and growth of the organisation. Thus, the case serves as an example of how gamification can be used to encourage stakeholders towards greater levels of sustainable attitudes and behaviours.

10.1 Introduction

Climate change brings an existential threat to life, and although largely contributed to by human behaviours, changing these habits has been proven difficult [1]. With all 193 United Nation member states [2] ascribing to the Agenda 2030 for sustainable development, this illustrates the urgency and awareness that economic growth needs to be aligned with sustainability principles [3]. This desired shift from unsustainable traditional linear production and consumption to more sustainable growth models

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is largely a result of recognition of the environmental challenges modern society faces [4]. The circular economy is an alternate economic model that seeks to keep materials and products in use for as long as possible while minimising waste. Some scholars, such as Edoria et al. [5], herald the circular economy as critical to ensuring the availability of future resources [5]. The role of individuals in a product's life cycle is a critical component of the circular economy due to their central behavioural role and the power they have in the choices they make [5–7]. Thus, understanding individual's attitudes and behaviours are vital for those seeking to establish circular behaviours within their business community.

A potential way of encouraging circular behaviours in individuals is via gamification. Gamification is relatively new field of study [8], defined as the application of game principles to a non-gaming context [1]. It can change individuals' behaviours by using the motivational drivers of reinforcement and emotion; these can be both positive and negative, as well as extrinsic and intrinsic, with the example of reinforcement being prizes [9]. The literature implies that because the effects of climate change are not instantaneous, individuals may not feel required to change their behaviour [1, 10]. Gamification may be able to tackle this via the provision of tangible pro-environmental goals that have instant rewards for completing the desired task [1]. This work aims to contribute to the literature via considering practical application of gamification theory to elicit shifts in working practices which thus achieve SDGs [11].

This paper examines a gamification system designed to encourage pro-environmental attitudes and behaviours, created by a higher education institution (HEI) in the United Kingdom (UK). The work examines gamification principles embedded into the initiative and how this directly results in the use of circular practices by both staff and students and considers whether these systems can contribute to achieving the United Nations (UN) Sustainable Development Goals (SDGs).

10.2 Literature Review

This literature review begins by examining corporations' motivations towards the implementation of circular principles, along with their connection to the wider strategic UN SDGs. Before considering gamification as a behavioural modifier and the connection to why individuals are more engaged in more sustainable actions.

10.2.1 Corporate Motivations Towards Circular Principles

Sustainability is a key concern for organisations due to changes in the environment, regulations, and pressure from society towards social and environmental responsibilities [12]. This is reflected in the legislation surrounding sustainability which is growing at a record pace. These pressures encourage organisations to take ownership of their social and environmental impacts, and for many corporations, sustainability has subsequently become an important part of organisational strategic goals [13].

In the search for more sustainable operations and growth, many organisations are looking to the circular economy as a potential solution, as it seeks to facilitate more sustainable production and consumption using circular principles [14]. The principle behind the circular economy is waste avoidance and a focus on recovery and reuse [15]. Circular principles can be categorised around the 7Rs: Reuse, Renew, Reduce, Redesign, Repair, Recycle and Retrieve [16]. All of these activities seek to either extend or close the loop in line with the core principle of the circular economy.

Triple bottom line (TBL) theory sees the success of any business measured not just in terms of finance, such as profits and return on investments, but also in terms of social and environmental dimensions [18, 19]. Under this philosophy, to implement effective, impactful and sustainable responsible strategies, businesses should have a broader picture of what the long-term goals of society are. In this respect, 'The Compact for Responsive and Responsible Leadership' sponsored by the International Business Council (IBC) of the Economic Forum states that "society is best served by corporations that have aligned their goals to the long-term goals of society", and it identifies the UN Sustainable Development Goals (SDGs) as the roadmap for that alignment [20]. The SDGs, sometimes referred to as the Global Goals, were enacted by the United Nations in 2015 as a global call to action to eradicate poverty and safeguard the environment. The 17 SDGs outline that development must balance social, economic and environmental sustainability and that actions in one area will have an impact on others [2]. To foster sustainable practices within business aligned with broader societal goals in an impactful manner, the IBC have developed a framework grounded in the SDGs, in the recognition that significant and transformative steps are needed to shift the world onto a sustainable and resilient path [20]. The framework by IBC encompasses the four fundamental pillars of the SDGs: Principles of Governance, Planet, People and Prosperity. This paper will examine the use of gamification to track clear progression towards these goals, which in turn seek to utilise circular principles in these actions.

10.2.2 Gamification

The principles behind gamification include the creation of clear progression with realistic goals and rewards that give players empowerment from their actions, utilising strategy and novelty to engage users, providing feedback that can be reinforced with comparisons and/or competition elements and fostering interaction between users. Often these principles can also be combined to optimise the system [1, 21, 22]. These principles foster intrinsic motivation for users to engage with the area in which behaviour change is being sought by the developer [1, 23].

The reward element of gamification, such as the acquisition of points along with the provision of feedback, has been found to be viewed more positively by users than when information alone is provided [1, 24].

Douglas and Brauer [1] reviewed gamification games and apps that have been empirically researched between 2017 and 2021. They find gamification to be a promising tool in the prevention of climate change. Their analysis suggests that there are four broad categorisations in the context of sustainability: sustainability education, energy reduction, transportation/air quality and waste management/water conservation.

10.2.3 Circular Behaviours

This paper draws on the unfavourable attitudes to sustainable consumption theory by Gbadamosi [25] along with the SHIFT model by White et al. [10] as psychological theories in line with why certain aspects of the gamification of sustainability are effective. Gbadamosi [25] proposes that there are six causes of unfavourable attitudes towards sustainable consumption: ignorance, fatalism, denial, cynicism, fatigue and disinterest [25]. This categorisation by Emery [26] is useful as it encompasses the many viewpoints which can cause individuals to shun sustainable actions. However, consideration of why individuals are not adopting sustainable attitudes does not strategically consider how they could be moved to pro-environmental attitudes and behaviours. White et al.'s [10] SHIFT model on the other hand presents a framework by which individuals can be encouraged to adopt more sustainable behaviours. Each component of the SHIFT model is an identified route to sustainable consumer behaviour change, derived from 280 article reviews. These five routes can be summarised as follows [10]:

- **Social Influence**: The presence, expectations and actions of others. Social factors such as social norms, social identities and social desirability have been found to be one of the most influential factors in eliciting sustainable consumer behaviours [27].
- **Habit Formation**: The formation of sustainable habit. Many sustainable behaviours need repeated actions that require new habit formation. Many typical habits not sustainable, therefore make sustainable habit formation vital [28]. To foster this sustainable habit formation, change of habit context, penalties, implementation intentions, simplification, prompts, incentives and feedback are all elements that contribute to the habit formation route.
- **Individual Self**: The desire of individuals is to maintain a positive self-view. Individual factors such as self-concept, self-interest, self-consistency, self-efficacy and personal norms play a crucial role in this route.
- **Feelings and Cognition**: Individuals may take one of the two routes, one driven by affect and the other by cognition [29]. For those taking the feeling route, positive emotions such as pleasure, joy, pride and optimism, or negative emotions such as sadness, fear and guilt may impact on pro-environmental decisions. Whereas those on the cognition route may find these decisions elicited via information and learning, eco-labelling and framing.

- **Tangibility**: Sustainability behaviours and impacts can seem abstract and removed from the self [30], therefore requiring individuals to remove self-focus and proximity thinking and focus instead on others and the future [31]. By matching temporal focus, this can help individuals visualise future benefits [10]. Communication of proximal impacts can add perceived relevancy [32] and immediate impacts [33]. Promotion of dematerialisation can also help to remove material possession as a focal goal of individuals.

10.3 Methodology

This paper adopts case study methodology, whereby the functions and features of the app were thematically analysed, relevant to the connected literature and themes. These relevant themes were connected to the specific real-world examples occurring within the app, while utilising holistic perspectives to further examine the core processes [34]. The core purpose is to examine the fundamental design choices of the app, considering why they were taken, how they were undertaken and what was implemented [35].

In this study, we are using the case of a higher education institution (HEI) and their Green initiative as a case. All organisations have vested interest in fostering sustainable growth, however HEIs are seen to have a critical role with regard to the SDGs due to their imbedded social responsibility and moral duty to develop social responsibility in their student community [34, 8, 11]. This scheme is seeking to impact behaviours from both student and staff. Our study consists of an analysis of the interface, examining the use of gamification to encourage circular practices, and uses the psychological theories by Emery [26] and White et al. [10] to determine the possible effects this has on changing consumer attitudes and behaviours to be more sustainable.

10.4 Case: The Green Points Scheme

When a user logs into the homepage of the green points scheme, they are instantly presented with an infographic showing their overall personal contribution, detailing the number of points they have earned, the number of actions they have taken, how many weeks they have contributed and the amount of CO_2 they have avoided. This infographic utilises gamification as it shows the user clear progression.

Below this, users are encouraged to record their actions to be awarded points. This is communicated with “take action, get rewarded” and clearly emphasises the principle of reward to try and motivate. With regard to the reward, five top preforming individuals receive a small monthly gift-card prize, along with an annual prize for the winning team (either student society or staff faculty team) of £100 to be gifted to a charity of their choice. A link to the ‘insight series’ of webinars is next to this, encouraging sustainability education—a category of sustainability gamification (1). Users are also encouraged to participate in this education by receiving reward points for each webinar watched.

The remaining homepage content is devoted to the gamification principle of competition and comparison, using the methods of a leader board with filters for individual scores, student societies or staff faculty teams. This leader board presents both the total points collected and the points for the month (with monthly prizes as a reward feature). This is supported with an interactive graph presenting the impact of these circular actions, filtered in respect to the individual, the team they are in and the overall for the HEI institution. To help users visualise this impact, they are presented with the kWh saved along with the number of average homes they could power with this saving a day, as well as the CO_2 prevented in kg. Users can collect green points via 6 categories which shall now be analysed in Table 10.1, before the unfavourable attitudes are examined in Table 10.2. Table 10.3 examines how the green scheme encouraged the adoption of more sustainable consumption (as defined by White et al. [10]).

10.5 Discussions and Conclusion

The green scheme analysed illustrates how gamification in all four of the categories of sustainability games and apps identified by Douglas and Brauer [1] can easily be incorporated by organisations seeking to encourage their stakeholders towards more sustainable actions. It also highlights how easily the gamification principles of progression, goals and rewards, as well as feedback, comparison, community interaction and competition can be intertwined into such schemes.

With regard to using the SDGs as a structural tool in such a scheme, it was found in this case that five of the seventeen SDGs were focused on within the six categories of the scheme. For organisations designing their own green schemes, all the SDGs should be considered, for example, where donation of unwanted items was included in the analysed app, donation to a food bank, or swapping unwanted food with a colleague could have been included to serve the SDG2 of zero hunger.

In terms of the Rs surrounding circular activities, these were found to be heavily under-utilised in this case, with only reuse, reduce, repair and recycle actions being encouraged. The remaining Rs of renew, redesign and retrieve provide valuable contributions to the circular economy, and actions such as re-painting or re-cleaning of old and dirty items could be included to encompass these remaining activity areas.

It was also found that the green scheme design covers the whole SHIFT framework developed by White et al. [10] to encourage users to adopt more sustainable behaviours. Such schemes can play an important role in bringing about change within organisations and in wider society through habit formation and improved knowledge.

With regard to the changing of unfavourable attitudes, it can be viewed that the scheme analysed is effective in targeting of four out of the six groups proposed by

Table 10.1 Analysis of the 6 categories of the green points scheme

Category	Actions available	App category	Circular principles	Linked SDG
Carbon saving	Switching off electrical equipment, reporting energy issue, reading energy saving tips, reading the HEI zero carbon plan, taking a carbon quiz, calculating personal carbon footprint	Energy reduction, waste management, education	Reduce, repair	SDG7 affordable and clean energy
Sustainable travel	Travelling actively, using public transport, using fuel saving techniques, car sharing, holding meetings online	Energy reduction, transportation/ air quality	Reduce	SDG11 sustainable cities and communities
Health and well-being	Reading the NHS five steps to mental well-being, growing plants, keeping active, taking outdoor breaks, exploring walks at the HEI, taking photos in the grounds of the HEI, remote working	Education	n/a	SDG3 good health and wellbeing
Waste and recycling	Reusing something at the HEI, donating unwanted items to charity, reducing food waste, taking a recycling quiz, using reusable cups, avoiding single use plastic, recycling, going paperless	Waste management, education	Reuse, recycle, reduce	SDG12 responsible consumption and production
Responsible purchasing	Purchasing fair trade, hosting a sustainable event, eating meat-free, reading about sustainable purchasing, shopping locally	Education	n/a	SDG12 responsible consumption and production
Promotional activities	Watching a video, taking a quiz, making a suggestion regarding sustainability at the HEI, promoting the scheme in emails	Education	n/a	SDG17 partnerships for the goals

Emery [26]. To target the remaining two groups (those who are fatalists or disinterested), the scheme would have to place much more emphasis on personal responsibility—perhaps even having to elicit emotions such as shame to push these individuals into action.

Further research should seek to investigate the interactions made by users with the different aspects of the scheme. Implications for the sustainable design community

Table 10.2 Analysis of how the green scheme approaches unfavourable attitudes

Unfavourable attitude	Green scheme response
Ignorance	The green scheme focuses heavily in this area with all the six categories of the scheme containing the possibility of gaining points through watching informational videos, taking part in webinars, reading articles and taking quizzes to test learning
Denial	By showing the CO_2 saved by the user's actions, this helps to illustrate the environmental impact of a human's actions
Cynicism	The use of the points in infographics illustrates to the users exactly what their actions have managed to achieve in real terms (i.e. how many homes can be powered for with the energy saved)
Fatigue	The fact that the scheme shows monthly and yearly achievement scores give the user the sense of longevity

Table 10.3 Analysis of how the green scheme encourages more sustainable behaviours

Encouragement	Green scheme response
Social influence	The designation of teams (student society or staff faculty) creates a sense of community and with that comes expectations and accountability. The social media sites for the scheme also encourage community norms. The leader board and prizes encourage interaction, comparison and competition
Habit formation	Users sign up to tasks they wish to complete, the system uses prompts each Friday for users to report their actions. Many of these tasks are recurring and lead to habit formation. The points awarded for consistent action and reporting act as incentive
Individual self	The individual figures allow the user to develop their personal norms and compare themselves to others in the community. If the individual has obtained the same or more points than their peers, this can enforce a positive self-view
Feelings and cognition	For those taking the feeling route, positive emotions obtained from completing tasks, or the guilt from not completing tasks encourage sustainable actions. For those taking the cognition route, there are many educational activities in the scheme
Tangibility	Many of the actions promote dematerialisation (such as donating unwanted goods or reusing objects), many actions also focus on the HEI campus allowing for proximity recognition

would be that such schemes can effectively use gamification principles to drive sustainable actions contributing to the circular economy and global SDGs.

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Chapter 11
The Production Capacities of *Cannabis sativa* and Its Growth Possibilities

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Abstract The authors report a detailed system analysis of the reasons why products derived from *Cannabis sativa* have found use as materials for green building. The causes of the greater attention to sustainability also in the building sector are discussed: (i) use of highly renewable resources, (ii) reduction of emissions, (iii) reintegration of waste into the production cycle, with a tendency toward zero waste. The evidence of these advantages is causing an effective diffusion of hemp in construction. In this regard, the authors report the data relating to the production and use of hemp in construction at a national, continental and world level. The analysis of these data demonstrates an evident increase which, however, appears to be characterized by considerable temporal fluctuations. In light of these historical data, the authors envisage on the one hand (i) the limited capacity to increase the production of *C. sativa* and on the other hand (ii) the increase in the requests for hemp-based products by the building sector. Also on the basis of the historical analysis of a case study (that of the *Edilcanapa* Company, Teramo, Italy), the authors demonstrate that the limits to the increase in the production of *C. sativa* can in turn represent a limit to its use in construction in the next years. The authors demonstrate an imminent imbalance between limits to production growth and an increase in the demand for hemp derivatives for construction purposes. In fact, despite the paucity of available data, our preliminary analysis highlights how the market of derivatives of *C. sativa* for construction purposes represents a critical production system and—at the same time—a rapidly expanding market, endowed with extraordinary incremental potential.

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11.1 Introduction

11.1.1 The Environmental Problem

During the twentieth and twenty-first centuries, the construction sector has had—and still has—a notably negative impact in the environmental pollution of Earth and in the massive consumption of non-renewable raw materials. According to the COP21 held in Paris, the building sector, globally, must commit to reducing carbon emissions to zero by 2050. The report of the 5th edition of the GABC—*Global Alliance for Buildings and Construction*—meeting showed that construction is the cause of 40% of total greenhouse gas emissions globally. Furthermore, construction absorbs 36% of the entire energy consumed worldwide, as well as causing 50% of the extraction of raw materials and consuming as much as 1/3 of the drinking water used in total [1].

In order to contain this situation and reduce the impact of the construction industry on the ecosystem, efforts have been made, both at a regulatory and design level, aiming at reducing the buildings' energy consumption [2]. The reduction must not only consider the energy consumed in the use phase [3], but also that embodied in the buildings (i.e., the energy used for the construction of the building and all its components). This effort translates into the use of low embodied energy building materials; materials of natural origin may respond optimally to this need [4], or even better, materials deriving from vegetable biomass (agricultural by-products, food and agricultural waste), as they do not require complex and lengthy manufacturing processes/production and their raw materials are carbon–neutral.

In this research a market analysis was carried out, conducted on a case study, to understand how much hemp was used and consequently processed for the construction of building products. The general objective is to verify the relationship between supply and demand on the hemp market in Italy.

Therefore, the authors present in this article the preliminary data of the rapidly increasing trend in the demand for hemp for green building by relating them to the very slow increase in agricultural hemp production, assessing for the first time the risk of an imbalance in the system and indicating which are the directions of scientific, technological, economic and legislative investments to avoid the imbalance between production and demand.

11.1.2 The Productive and Scientific Interest in Hemp-Based Building Materials

For generating a new green construction industry, therefore, the interest in hemp as a raw material has increased.

On a general and global level, there are currently more than 30,000 products that can be made from the processing of *C. sativa*: from products for the textile and paper industry, to hemp oil for bioplastics, cosmetics, food. On the other hand, the hemp waste can be used as biomass and in the building sector for the production of waxes, fixatives, paints, plasters, insulating panels, blocks and mortars [5]. The commercial interest connected to hemp, has also encouraged scientific studies. In particular, researchers focused on two main aspects: (i) the characteristics of the plant cultivation and (ii) the characteristics of hemp products for building purposes. Although an exhaustive analysis of the literature goes beyond the scope of the present work, it is appropriate to summarize the fundamental works related to this field, in order to provide a framework to better understand the sector. The literature analyzed for this article was selected from the Google Scholar database. Keywords were used to search for articles: Hemp Shives, Block e Cultivation, Hemp, Building. With regard to raw material production, Karus and Vogt [6] reported the results of market surveys conducted by the *European Industrial Hemp Association*—EIHA—on the cultivation, production and product lines of hemp in Europe [6]. Vilcina et al. [7] noted the current developments of the hemp industry in the European Union and Latvia, proposing a general description of the development trends of the hemp industry in the European Union, also analyzing the potential growth of the hemp industry in Latvia [7]. Jonaitiene et al. [8] proposed an analysis of the possibilities and prospects of expanding consumption and production of hemp-based products and, consequently, cultivation in Lithuania [8]. Adesina et al. [9] proposed a review of the benefits of hemp plantations and identified future research needs regarding the cultivation of multifunctional crop to meet growing market demands [9]. Rehaman et al. [10] proposed a detailed review on the uses of industrial hemp, also reporting an updated report on the multi-functionality of hemp cultivation, benefits, uses, growth constraints and potential improvement strategies [10]. Karchel and Singh [11] demonstrated how hemp can represent a “cash crop”, capable of minimizing environmental and human health issues. The authors analyzed the commercial, industrial and agricultural potential of hemp with the aim of promoting its cultivation and increasing the use of its derived products [11]. In the experimental field aimed at ascertaining the physical, chemical and environmental qualities of hemp for building purposes, Cigasova et al. [12] developed and published evaluation tests of lightweight composites based on hemp fibers and MgO-cement binder [12]. Furthermore, Scrucca et al. [13] performed an accurate energetic and environmental assessment of hemp cultivation in France [13]. Finally, Jami et al. [14] reported the vast majority of known information on various properties of hemp concrete and its applications in building construction [14]. Barbhuiya and Bhusan Das [15] published a review on the rapidly developing body of knowledge on hemp concrete [15].

11.1.3 Scenarios for the Increase in Demand for Hemp-Based Building Products

The increased interest in hemp building products expressed by researchers, entrepreneurs, global market and consumers, who are increasingly focused on environmental issues, may lead to an increase in their use in the field of bio-architecture. This should correspond to an increase in market demand and, consequently, an increase in the production of the raw material and its derivatives, or a growth in the cultivation of hemp. The purpose of this article is therefore to investigate the sustainability and possibilities of hemp cultivation, in a scenario of its increasing use in the construction sector, in the Italian territorial context.

11.2 Materials and Methods

The analysis originates from the observation of data retrieved from the literature relating to the trend of hemp cultivation at a global, European and Italian level in recent decades. This observation is the general basis for a more in-depth analysis of the historical and current scenario in Italy. The data has been completed with a market analysis, conducted on a case study, to understand how much hemp was used and consequently processed for the construction of building products. The case study examined is the Teramo-based company *Edilcanapa* (Teramo–Italy). The data collected by the Company had been used to estimate the annual consumption of raw materials by the Company itself.

The data obtained from the literature review were compared with the Istat (*Italian National Institute of Statistics*) data relating to the cultivation of hemp from 2012 (the year the *Edilcanapa* project was launched) to 2022, and were confronted with the uses of raw material by *Edilcanapa* Company. The goal was to understand the relationship between the cultivation trend and the company's demand for raw materials within the previously mentioned time frame. Based on the results of this first phase, we hypothesized a scenario on future trends regarding the demand for raw material and hemp cultivation, to better understand if the two aspects are related and if there is a real chance of growth of the use of hemp in the green building sector in the Italian panorama.

11.3 Observation

11.3.1 Properties of **Cannabis sativa**

Hemp has a number of properties that make it a potentially eco-sustainable material throughout its life cycle, considering both its cultivation (it's a very strong and resistant plant, with very rapid growth times, whose seeds are able to germinate and grow at any latitude, allowing a saving of 90% of water compared to that generally used for the production of cement, and just under a third of energy; it does not require the application of pesticides, herbicides and fertilizers; it is able to regenerate the land on which it is grown and is able to capture large quantities of carbon dioxide from the atmosphere) and the constructive point of view. In fact, these are products from renewable resources, recyclable, resistant to mold and insects, resistant to rodents, excellent thermo-acoustic insulators, with good natural fireproof properties, with high thermal inertia, resistant to freeze and thaw cycles, highly breathable, rich in silica, with low hallucinogenic content, do not contain VOCs—Volatile Organ Components, durable over time, light—about one-seventh or one-eighth the weight of concrete, excellent performance in case of seismic events, suitable for self-construction as they do not require complex construction methods [5], carbon negative (each ton of hemp absorbs a quantity of CO2 that can vary between 1.7 and 1.9 tons) and potentially at Km 0.

Consequently, hemp as a raw material and its building products derivatives appear to be interesting for the development and diffusion of *green* building.

It should be noted that, in the building sector, it is mainly used the hemp stem, which represents 60/70% of the total plant [16], from which the shives and fibers are obtained.

11.3.2 History of **Cannabis** *in Italy*

In Italy, the first finds of *Cannabis* pollen date back to 11,000 BC, in Lazio, near Lake Albano [17]. In Roman times, hemp was used for making ropes and canvases. In fact, the extensive cultivation and use of hemp fiber was closely linked to the expansion of the *Maritime Republics*, as hemp served and still serves as a raw material for making ropes and sails for boats (the cordage of the historic ship Amerigo Vespucci—1931 [17]). And this is the most flourishing period for the cultivation of hemp in Italy, especially in the Bologna area and in the surroundings of the city of Ferrara. But the use of hemp for war fleets was accompanied by trade with Asian cities and the export of hemp and its products to Northern Europe (Italy was the first supplier of hemp products to the British navy). This was possible thanks to the widespread diffusion of hemp cultivation and the quality of the grown and processed product, so much so that Italy was the second largest producer of hemp worldwide, after Russia [18].

Slowdown in the Cultivation and Production of Hemp-Based Products

Historically, starting from the nineteenth century, the cultivation and production of industrial hemp-based products experienced various phases of arrest. For instance, in Italy, the thriving production slowed down sharply due to the advent of coal-fired ships, which no longer required sails, often made from hemp fiber.

In the 1930s, in the United States *Cannabis* was accused of fueling heinous crimes during those years and the term *Cannabis* was replaced with *marijuana*, to the extent that in 1937 a law was passed prohibiting the cultivation of every species of hemp (*prohibition*). After the Second World War, this situation spread throughout the world, almost bringing to an end *Cannabis* use for medical and industrial purposes. In addition, 1937 saw the introduction of the *Marijuana Tax Act*, which significantly increased the costs of growing *Cannabis* [16] and thus benefited the production and use of synthetic fibers. In the 1961, the approval of the *Single Convention on Narcotic Substances Act* led to the near disappearance of the cultivation of *Cannabis.*

The Resurgence of Hemp

Starting from the mid-1990s, a rediscovery of the *Cannabis* plant has been underway, along with a rising awareness of its environmental and economic benefits. Gradually, new crops and new and innovative production chains have arisen, with interest continuing to grow and involve not only agricultural companies, but also institutions and research bodies spanning countries in North America, Europe and Asia, including China and India [16]. Unfortunately, in Italy the long period of suspension in hemp production led to a total loss of cultivation and processing techniques, and consequently resumption of production has been particularly long and slow.

11.3.3 Hemp Today

At European level, the *European Industrial Hemp Association* (EIHA) was founded in 2005, a pan-European body in support of companies that produce, process and distribute hemp and its derivatives [18].

According to the 2019 EIHA report, in 2018 the total area of hemp plantations over the whole of European territory consisted of 58,000 hectares [19], a figure that underlines an increase in cultivation of 3.3% as compared to the 2017 EIHA report. Compared to 1993, however, the increase was 614%. The increase in cultivation recorded in 2018 sees France in the lead at 17,900 hectares of cultivated land, equivalent to 37% of the entire European cultivation. France is followed by Italy, with 4,000 hectares of cultivated land, or 8% of the entire European cultivation area [20].

The increase in production that we are witnessing is also the result of new countries joining the European Union. This has helped to place Europe in third place for hemp-growing areas worldwide, with 58,000 hectares (data relating to 2018), behind only China and the USA [19]. This increase has also led to an increase in the industrial use of hemp, since it is considered a suitable alternative to other materials in sectors such as textiles, agri-foods and construction, as well as a cultivation model and supply chain for a sustainable, resilient and circular economy.

Daniel Kruse, President of the EIHA, notably stated that "*A new agricultural revolution is knocking at our door and the hemp sector is more than ready to embrace it. We hope the EU will follow market trends and implement those regulatory changes capable of attracting the necessary investments needed for scaling up the production and marketing of hemp products.*"

The recent 2022 *InterChanvre*[1] report, relating to the production of hemp in 2020, showed a reduction at European level of 7.86% (in just one year) in the cultivation of *Cannabis*, falling to 53,624 hectares. In this reference year, a number of countries, such as France, Estonia and Lithuania increased the land area cultivated with hemp, while others, including Italy, decreased cultivation. Specifically, the area of Italian hemp plantations fell from 5,000 to 1,500 hectares [21]. Despite the reduction documented between 2019 and 2020, Europe has recently moved into second place in world hemp cultivation. This upward shift in the global ranking is due to a drastic reduction in the cultivation of *Cannabis* in the USA (from 59,000 to 29,137 hectares), as recorded in the latest 2022 report relating to crops in 2020 [21].

Globally, studies based on the doubling of the population have predicted an increase in the demand for fibers (natural and non-natural) of approximately 260%, going from the current annual demand of 50 million to 130 million tons by 2050 [22].

Cannabis Cultivation in Italy

Up until the Second World War, Italy, at European level, was second only to Russia for land area cultivated with hemp, while it was in first place for yield per hectare [18]. This situation changed dramatically due to prohibitionist dynamics and lack of mechanization in hemp production and processing, leading to an abandonment of cultivation in Italy.

Following the end of prohibition and starting from the 1990s, hemp was gradually reintroduced in Italy in two key sectors: (i) textiles and (ii) construction. In 1998, the entire area cultivated with *Cannabis* in Italy stood at 350 hectares [23]. This modest recovery of the hemp agricultural sector was due to a 1997 Circular issued by the Ministry of Agricultural Policies: the *General Directorate of National Agricultural and Agro-industrial Policies*. The circular defined the methods farmers should adopt to avoid confusion between industrial hemp and that used for drugs, with the constraint that only the long fibers used as raw material for textiles and ropes could be marketed. [23]

At present, Italy is undergoing an increase in cultivation and processing of hemp, considering that 92.7% of cultivation arose over the past five years, of which more than 50% arose over the latter two years (data updated to 2016) [18].

According to a survey published in 2016, involving 41 hemp producers throughout Italy, the quantity of hemp destined for the green building sector stands at 43.9%, a

[1] InterChanvre is the French association that brings together all *stakeholders* involved in the hemp industry.

percentage that could grow further considering that, often, the part of the plant used for the production of building products is abandoned on cultivated land as waste material [18].

Even in Italy, as seen previously in the case of Europe, various associations have arisen to support and promote companies in the hemp business. One of the most relevant is certainly *Assocanapa*, which has been operating throughout the country since 1998.

11.4 Results and Discussion

From what we have seen so far from previous studies and from LCA analyses conducted by experts, we can start from the assumption that the cultivation of hemp, in addition to having innumerable advantages, is growing rapidly, just as we can be confident the products based on hemp have innumerable beneficial properties and therefore could assume a pivotal role within green construction over the coming years. However, can the current production trends of hemp in Italy support the increase in demand for raw material due to an increase in demand for hemp-based building products as a result of wider use on a national scale of these products in the green construction sector?

To try and answer this question, the present study examined the data published by Istat concerning the cultivation of hemp in Italy from 2012 to 2022 as well as the related total production in quintals (see Figs. 11.1 and 11.2). From these data it emerges that, following a period of clear growth in the area cultivated with hemp from 2012 to 2016, there was an important setback in 2017, with −272 hectares fewer as compared to the previous year alone, which boasted a +199 hectares increase compared to 2015. In 2018, there was a rise in cultivated hectares, with a variation of +211 hectares as compared to 2017, followed by +237 hectares in 2019 as compared to 2018. There was another reduction in 2020, likely due to the pandemic, with a drop in cultivation of −298 hectares as compared to 2019. This heralded a downward trend that saw a further reduction of −6 hectares of cultivated land in 2021 as compared to 2020. The observed reduction starting in 2020 continued until 2022, when there was a loss of −116 hectares of cultivated land as compared to 2021. Clearly the same trend is visible in the total production of hemp, expressed in quintals.

Given the trend over the past few years of cultivation and total production of hemp as a raw material for the various sectors in which it is used in Italy, it is possible to make a projection of the direction the trend might take over the next five years (2023–2027). From the arithmetic mean of the Istat data on the annual variations in the area cultivated with hemp in Italy, and without considering any disruptions, an average annual growth rate of approximately +47.8 hectares can be calculated. While for harvested production, an average annual growth rate of approximately + 3956.9 quintals can be calculated on the basis of the annual variations in the quantities produced.

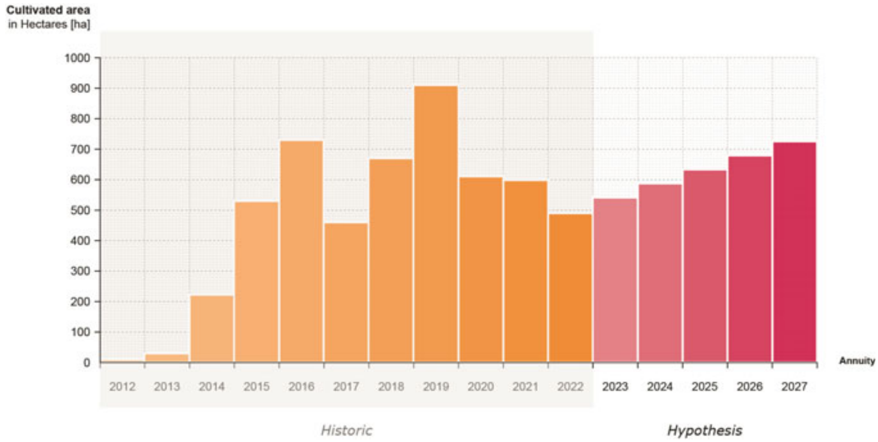

Fig. 11.1 Diagram on the trend of hemp cultivation in Italy, in hectares, from 2012 to 2022 [24] with assumptions of surface increase over the next five years, from 2023 to 2027. The growth trend, represented in the diagram, was assumed from the average annual increase of previous years (2012–2022)

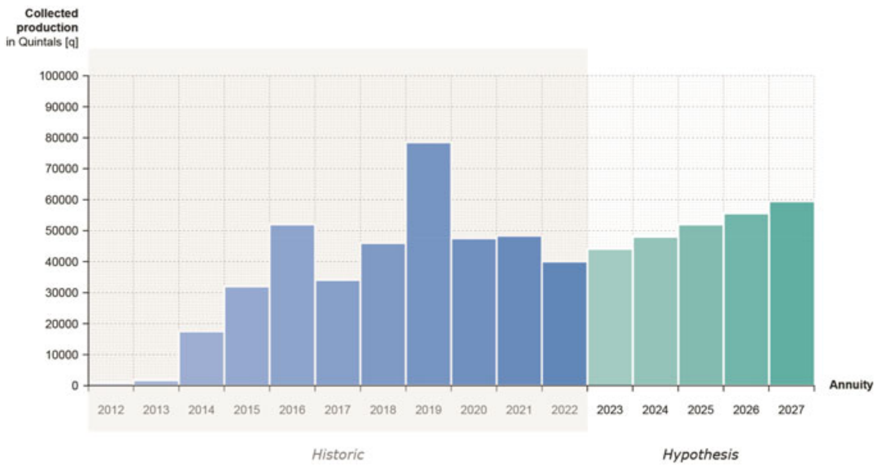

Fig. 11.2 Diagram showing the trend expressed in quintals in the production of raw materials (flowers, leaves, stems) in Italy from 2012 to 2022 [24] and hypothesized increase over the next five years, from 2023 to 2027. The growth trend, represented in the diagram, was assumed from the average annual increase of the previous years (2012–2022)

This leads us to predict that, very likely, in 2027 the area cultivated in Italy could amount to around 726 hectares (see Fig. 11.1), with a total production of 59,803.5 quintals (see Fig. 11.2). These estimates should be understood as being net of fluctuations, which also marked the trend of production over the past decade.

On the other hand, the consumption of hemp, as a raw material, was also taken into account by examining the data from the case study, i.e., of the partner company *Edilcanapa*, from the year of its foundation in 2014 up until 2022. It should be noted that at present the Company manufactures building products only to order, with the aim of optimizing production and avoiding accumulation of unsold goods. As a result, all the raw material purchased (shives and fibers) is transformed into product already sold, without retention of stock.

From the analysis (see Fig. 11.3), it emerged that in the early years dedicated to studies into the potential of hemp as well as market analysis and product development, there was no demand for material by the Company. The first orders for both the shives and fiber necessary for the production of various building products were placed in 2017. As a result, the trend in demand over the 5 years from 2018 to 2022 grew steadily, with a maximum increase in 2021, while in 2022 there was a small reduction in the purchase and use of raw materials. In this analysis it is important to underline that during its early years *Edilcanapa* sourced its raw material abroad from other European Community countries (France), while only in brief periods in 2021 and 2022 did it use raw material from Italy (up to now this had not been possible due to the quality of Italian raw material, which did not meet the standards required by the Company).

Based on these changes from 2018 to 2022, an average growth rate of +62.56% per year was calculated.

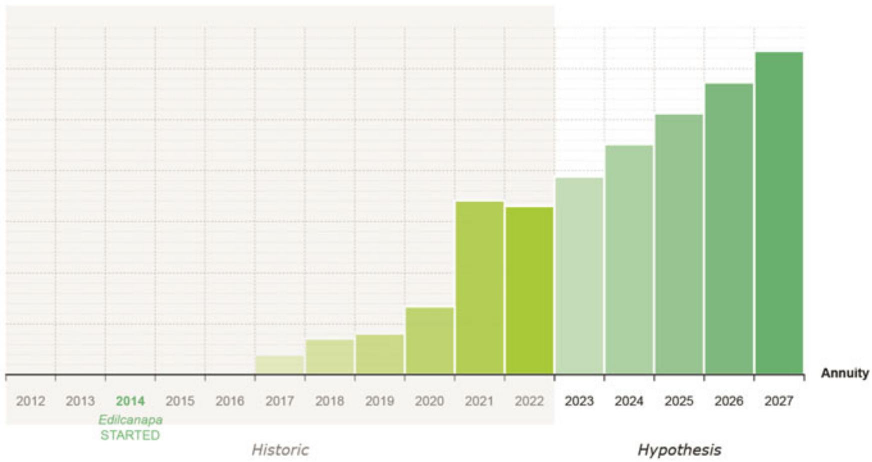

Fig. 11.3 The first part of the diagram (left) shows the quantities (in quintals) of hemp used by *Edilcanapa* from 2014 to 2022 for the production of building materials. The second part of the diagram (right) shows the hypothesized increase in hemp used by *Edilcanapa* over the next five years (2023–2027) for the production of building products. The growth trend, represented in the diagram, was assumed from the average annual increase over previous years. The absolute values of raw material used are not shown in the graph due to company confidentiality

Given the trend in demand for hemp by *Edilcanapa* over the five-year period 2018–2022, a projection was made of what the Company's demand for raw material might be over the next five years (2023–2027). From the weighted average of the annual variations of raw material used by the *Edilcanapa*, without taking into account possible disruptions, a hypothetical increase in demand on an annual basis of + 17.6% compared to 2022 value (corresponding to the average annual growth rate) was calculated, for a total of approximately 88% in 2027 compared to 2022 (see Fig. 11.3).

11.5 Conclusions

From the overlapping and reading of the trend hypotheses regarding the cultivation and total production of hemp and the demand by the Company taken as case study, it emerged that if in the next five years (2023–2027) the market were to maintain the trend of previous years (2018–2022), thereby showing an annual increase on the order of 47–50 hectares of cultivation (equal to about 9.8% annual increase compared to 2022), with 39.569 quintals of total hemp production (also equal to about 9.9% annual increase compared to 2022) and an annual increase in demand by *Edilcanapa* for raw material on the order of 17.6%, the market supply and demand system will not be able to sustain itself. Assuming that the data emerging from our case study reflect the national situation, this implies that if there is indeed an increase in the large-scale use of hemp-based building products in Italy, yet production of raw material (cultivation and primary processing) maintains the growth trend seen in the past, the production system will not be able to sustain itself to supply the necessary raw material. Consequently, if we are determined that hemp-based building products should become fundamental to the *future* of Italian green construction, it is necessary to increase the cultivation of *C. sativa* in Italy.

The current growth in the use and demand for industrial hemp and the need to act in favor of the environment will certainly lead to an increase in its cultivation and subsequent processing for the production of goods.

The current criticalities of this growth and development of the hemp sector are, however, several: (i) the deficiencies in the structure of the entire supply chain, which should be a zero kilometer supply chain; (ii) regulatory shortcomings at European and Italian level (with often unclear and uneven rules); (iii) the lack of knowledge and skills in the various phases, from initial project, to processing, to implementation; (iv) prejudices against *Cannabis*, accentuated by a complex and often unclear bureaucratic apparatus [16]; and (v) the absence or low demand from insiders (companies, designers and retailers) of hemp-based building products.

The system analysis conducted on the supply and demand of the hemp market as a raw material for the production of different products, can be deepened in a second phase by undertaking a detailed analysis. Such analysis, which is beyond the scope of this study, requires the availability of the absolute quantities of raw material (hemp) used by *Edilcanapa*, which are currently withheld in line with trade secrecy.

Furthermore, it will be necessary to assess the quality of the hemp produced in Italy in general. A mass allocation and ranking will be required between all the co-products deriving from the cultivation of hemp (flowers, seeds, fibers, shives, powders), since co-products vary according to the type of *Cannabis* grown.

In conclusion, if our preliminary data on the rapid increase in the demand for hemp are representative of a trend, there is no doubt that the production vs. use system will be unbalanced in the next two or three years: this is the result of an exponential increasing attention to hemp as a leading product of green building, but the next economic and legislative efforts must be focused quickly to obtain a strong increase in agricultural hemp production.

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24. Istat: 2023

Chapter 12
The Most Appealing Steps Towards Decarbonisation for SMEs in the UK

Elisha Rasif, Katie Louise Leggett, and Chris Ivory

Abstract This paper aims to examine current efforts of small and medium-sized enterprises (SMEs) in the UK towards decarbonisation using the circular economy principles. Business operations are at the heart of decarbonisation, and the reduction and removal of carbon dioxide output from operations is currently a key concern. This study subsequently analyses which energy choices and circular economy (CE) practices have been the most attractive option, along with the overall long-term sustainability of these choices. A facilitated workshop methodology was undertaken with SMEs already using CE principles to improve their sustainability credentials and lowering their carbon footprint. The results led to the identification that solar energy has been chosen as the key focus towards greener energy, with the reduction of materials used in operations as the primary CE practice. These are easier actions that do not disrupt current operations; however, for longer-term sustainability, stronger actions like closing material loops will be needed.

12.1 Introduction

With businesses looking to become more sustainable, a transition to circular economy activities has become an appealing choice. With the circular economy being a consumption and production model, which endeavours to keep material and products in use for as long as possible, while keeping waste minimal [1]. One of the most influential factors towards this drive for more sustainable practices is climate change. Climate change and global warming are considered to be the result of anthropogenic greenhouse gases, with carbon dioxide (CO_2) being the most prominent [2]. CO_2 forms approximately 80% of greenhouse gas emissions in the United Kingdom, mainly released from the combustion of fossil fuels to release chemical energy [3].

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A granular analysis of climate change related to the combustion of fossil fuels indicated a high likelihood of dramatic increase in temperature, wet-bulb temperature, and precipitation, which would have a severely negative impact on the health of individuals—particularly the young, elderly, poor and marginalised [4]. In response to this impact on the environment and health, focus and policies have turned towards decarbonisation.

Decarbonisation is the process of stopping or reducing carbon gases, particularly CO_2, from being released into the atmosphere as the result of a process—such as the combustion of fossil fuels [5]. It can also be defined with a specific focus of it being the reducing and removal of CO_2 output from a country's economy [6]. The UK Governments Net Zero Strategy to build back greener consists of policies and proposals for the decarbonisation of all sectors of the UK economy to meet a goal of net zero by 2050 [7]. Therefore, increasing the understanding of what steps businesses are taking towards this goal is important, for both understanding which routes are the most accessible and which are not being utilised.

The business sector in the United Kingdom contributes roughly the same percentage of emissions as the residential sector (18% and 19% respectively), so the transition of businesses towards more sustainable energy use can have a large impact on the drive to decarbonisation [3]. In this paper, we examine how small and medium enterprises (SMEs) in the UK are currently tackling their carbon emissions and seek to critically evaluate the routes to decarbonisation they are choosing and the long-term sustainability of these choices. The examination of SMEs was chosen as they constitute most private sector businesses in the UK—with 5.5 million small businesses and 35,600 medium-sized businesses in 2021 [7], thus making their potential impact on decarbonisation considerable. To complement this, a facilitated workshop methodology was chosen for the authentic collaboration this method enables, while also benefitting participant interests alongside fulfilling the research purpose [8]. The sample consists of SMEs who are aware of their carbon footprint and are actively seeking decarbonisation. The findings of this study can help to inform and inspire other SME's towards reduction of carbon emissions; as a recent report indicated that nine out of 10 SMEs are unaware of their business' total carbon emissions, and 45% recognised the importance of reducing their emissions imminently given the current environmental situation [9].

12.2 Background

This background focuses on exploring how the circular economy can be used by SMEs to promote decarbonisation. Firstly, via specific activities which embody circular economy principles, followed by an examination of the forms of cleaner energy sources which are available. Finally, the barriers for SMEs to implementing these are discussed.

12.2.1 Circular Economy Activities and SMEs

The CE seeks to promote circularity in systems to keep materials in use for as long as possible and reduce waste, including the waste of energy. The circular nature of this model also promotes the positive use of 'unwanted' resources—such as carbon dioxide and other greenhouse gases [10]. One established theory in relation to CE practices is that of the 7Rs, which are Redesign, Reduce, Reuse, Renew, Repair, Recycle and Retrieve [11]. All these Rs are recognised as CE practices as they seek to close or extend the loop of resource flow [12]. SMEs are becoming increasingly aware of the reported benefits of closing resource loops and reducing resource waste [13]. However, there are limited studies specifically related to the actions SMEs have chosen to take [14]. The unit fabric can be a source of decarbonisation for SMEs, through consideration of the material properties. For the construction of new areas, new eco-friendly materials can be chosen. With regard to structures which are already standing, SMEs can assess modifications, such as the increase of insulation to prevent heat loss which will in turn require less energy use to maintain the desired internal temperature (using the Reduce principle). Whereas with regard to business operations, there is more scope for CE principles, for example, recycling resources, identifying materials or components which can be reused, rental of equipment rather than purchasing, etc.

12.2.2 Cleaner Energy Sources for SMEs

It can be argued that one of the conditions of sustainable development is that materials which are finite—such as fossil fuels—should not be extracted at a faster rate than which they can redeposit in the Earth's crust [15]. The current dominating role that fossil fuels play in the world's energy consumption is not sustainable, nor is it healthy for the environment [2]. Although SMEs cannot dictate how national power is generated, there are several pathways they can take in order to decarbonise, which this study focuses upon. Major potential routes with regard to decarbonising energy are:

- **Solar Panels**: A standard 4 kW solar photovoltaic (PV) array system, can generate 3400 kWh of electricity per year [16]. Surplus energy can feed into a central battery storage unit to provide electricity when needed [17]. Costs can be recouped in approximately 10 to 13 years, so the total lifespan of each unit is therefore also a consideration, and whether the panels could be reused on new units if required [18].
- **Wind Turbines**: Can be pole mounted or attached to the building structures. These attachments can generate between 3600 and 9000 kWh per year [19]. One turbine could theoretically provide enough power for one small business unit, with the ability to store any extra power in a battery.

- **Ground Source Heat Pumps (GSHP)**: An off-Grid solution for heat and when combined with PVs, they can provide an all-electric and heating solution. PV-assisted GSHPs have longer payback duration (8.5–23 years) compared to regular GSHP (5.8–16 years) [20].
- **Air Source Heat Pumps**: They do not require excavation; however, they need indoor and outdoor space for the pump and boiler units. The installation cost ranges between £7000 and £13,000 [21].
- **Liquefied Petroleum Gas (LGP)**: LPG is stored in on-site tanks, with the cost of LPG fluctuating significantly. LPG has a low initial cost, but it incurs higher running and maintenance expenses than grid electricity, while having a lower carbon footprint than oil [22].
- **BioLPG**: In addition to being good for the environment, the transition from LPG to BioLPG is not complex. It is used in the same way and can be dropped into an existing supply with no changes to infrastructure. With up to 90% reduction in carbon emissions, BioLPG offers a cleaner, more environmentally friendly energy solution [23].
- **Solar Water Heating System (SWHS)**: Has an efficiency of approximately 70%, whereas solar has an efficiency of only 17% [24]. Despite their higher efficiency, SWHSs have a higher initial cost compared to conventional water heating systems [25].
- **Radiant Heating (Wet or Dry Systems)**: Radiant heating can be provided through underfloor or in-wall systems, using wet or dry methods. They are more energy-efficient than fixed radiators due to their larger surface area and heat spaces more effectively [26].
- **Combined Heat and Power (CHP) Boilers**: Generating electricity and heat simultaneously, with a ratio of approximately 1:6, results in cost savings [21]. They are highly efficient and can lower emissions by as much as 30% when compared to the separate generation of heat and power [27].

12.2.3 Barriers for SMEs Seeking to Use CE Practices to Decarbonise

According to the 2021 Business Population Estimates, there were nearly 5.6 million businesses in the UK, contributing 52% of the turnover of UK plc, which is equivalent to £2,300 billion [7]. With their significant role in the economy, SMEs also have a significant impact on the environment; for example, in the UK, they reportedly emit 43–53% of the industry-driven greenhouse gas [28]. Despite this pollution rate, the uptake in CE by SMEs is not moving at the desired pace due to financial constraints and pressure from customers and policymakers. Several barriers to CE adoption among SMEs have been identified in prior research, including insufficient financial support, inadequate information management systems, lack of proper technology and technical resources, limited financial resources, low consumer interest in the environment, inadequate support from public institutions, shortage of qualified environmental management professionals and inadequate commitment from organisational management [29, 30]. According to Kirchherr et al. [31], the main obstacles to adopting CE are cultural barriers such as consumers' lack of interest and awareness, and a hesitant company culture [31]. SMEs may perceive decarbonisation efforts as risky due to uncertainties around new technologies or concerns about potential business disruptions [28]. These cultural barriers are fuelled by market barriers, which are caused by insufficient government interventions. As noted by Perez-Batres et al. [32], while transitioning to renewable energy is seen as the optimal method for UK SMEs to achieve carbon neutrality and potentially lower energy expenses, they still require financial assistance to implement these technologies [32].

12.3 Data and Methodology

To understand which changes towards sustainability have been undertaken by SMEs in the UK, a facilitated workshop methodology was used with ten SME representatives who are all actively seeking decarbonisation. Facilitated workshops as a research methodology focus on the study of domain-related cases using the workshop format as a research methodology. Facilitated workshops are authentic as they seek to enable the participants to achieve something related to their interests, while also carefully designed to fulfil a research purpose, providing a reliable and valid data set about the domain in focus [8]. Three 2-h workshops were conducted, each comprising of 10 SMEs engaged participants in discussions on change strategies and barriers to decarbonisation in relation to their organisational needs. To strengthen discussion and call to action, support was provided through carbon footprint analysis (CFA). Data from the CFAs enabled discovery of opportunities for change and helped gain insights into barriers faced by the local businesses. This method was appropriate as when used as a research methodology, facilitated workshops aim to produce reliable and valid data regarding forward-oriented processes, such as the shift towards more sustainable business practices and the changes required and are characterised as emerging [8, 33].

12.4 Results

The results from the facilitated workshop found that only two key areas of the circular economy had been undertaken by the SMEs—the use of cleaner energy and the reduction of waste from production activities.

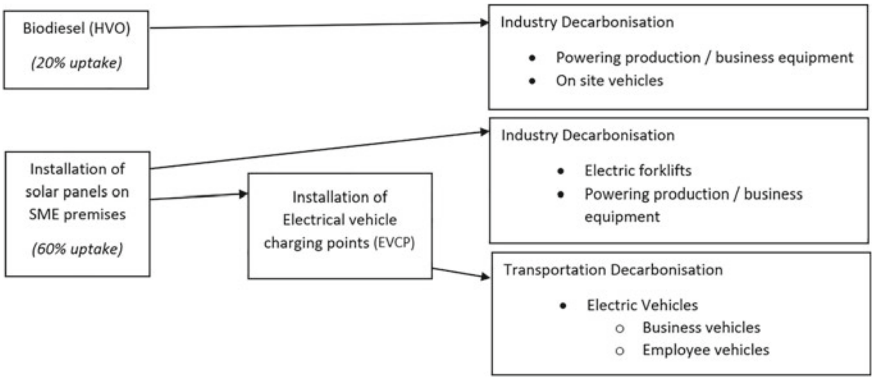

Fig. 12.1 Current energy decarbonisation routes undertaken by the UK SMEs

12.4.1 Cleaner Energy Sources

As can be seen in Fig. 12.1, it was found that only two alternative energy sources have been currently adopted, which are solar and biodiesel. Most of the SMEs have adopted solar, specifically from their own solar panels installed onto their premises. With only two SMEs having chosen to use biodiesel, both of which use this in combination with solar rather than as a standalone solution.

The power generated from these solar panels are decarbonising business operations, however there is also transportation decarbonisation with these businesses also installing electric vehicle charging stations, particularly as this allows employees to reduce their own carbon emissions with their personal electric vehicles (EVs).

Thus, only two routes to energy decarbonisation were found as a current pathway to energy decarbonisation followed by these SMEs. However, these SMEs are predominantly relying only on solar as a source of alternative energy. This source allows them to decarbonise in multiple areas—industry decarbonisation from renewable energy fuelling operations and transportation decarbonisation which also requires the installation of electric vehicle charging points (EVCP).

The participants were also keen to emphasise that they wish to increase their efforts towards solar energy by increasing the number of solar panels, EVCPs and business-use EVs. In particular, solar energy was at the forefront of their future intentions.

12.4.2 Reduction of Waste

It was also found that one of the ten companies is also focusing on the circular economy principle of reducing waste, specifically the reuse of factory water leading

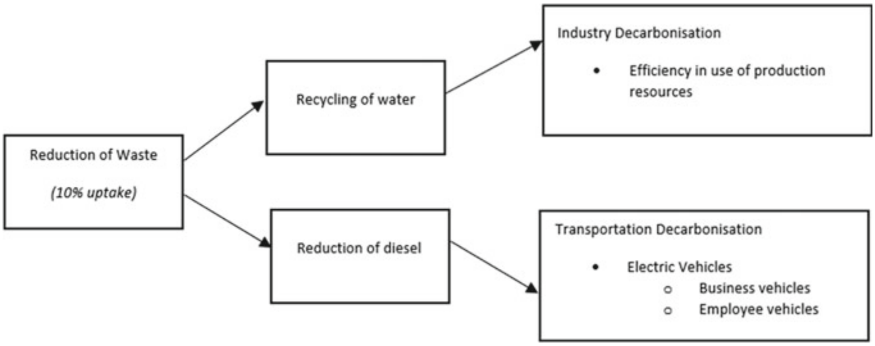

Fig. 12.2 Current reduction of waste routes undertaken by the UK SMEs

to less waste, along with the reduction of diesel due to the use of electric vehicles. This is presented in Fig. 12.2.

12.5 Discussion

It's clear that the firms engaged with were interested in decarbonising—and as such, they were indeed a self-selecting sample of firms that wanted to do something about their carbon footprint. This makes it even more interesting that they had done so little. What they had done was also revealing—pursuing what might be termed 'low-hanging fruit'. They had followed strategies which involved only mature technologies—those with relatively certain payback periods, costs and predicted reliability. In other words, it was a path of low resistance and low risk. This tells us something about the sorts of policies that are needed to encourage the uptake of carbon-reducing technologies and practices. It means, for example, that the government needs to put more money into developing, certifying and regulating the technologies which can achieve these ends. Policymakers and technologists need to think in terms of technologies that create 'appealing' (easy to follow, secure and rewarding) paths for firms. Certainly, it is not helpful to accuse firms of being 'hesitant' [31] when so many of the potential paths available are unclear and therefore appear risk-laden to firm decision-makers. Managers do not voluntarily make strategic choices that they feel may put the firm at risk [34]. Technology suppliers and government clearly need to take more responsibility for de-risking the paths to technology adoption in a way that will make them more appealing to firms.

12.6 Conclusion

It is reported that SMEs can reduce their environmental impact by embracing circular economy practices, although economic and social performance outcomes are not necessarily always guaranteed [35]. High financial outlay can be seen as a major barrier for SMEs to undertake CE practices [29], along with the disruption changing practices can cause to business operations [28]. We conducted a workshop with 10 SMEs from the UK's East Anglia region to explore what CE practices they have implemented in their desire to reduce their carbon footprint.

With the production of electricity being the largest cause of CO_2 emissions, alternative electricity production methods make an obvious focus for the shift towards more sustainable energy sources [2]. For SMEs decarbonising by generating their own green electricity for daily operation needs is attractive, as after initial equipment costs, their need to purchase electricity from the national-grid is greatly reduced or eliminated. The use of solar panels is also an attractive option as they are readily available and do not generate noise pollution—unlike many alternative options such as wind turbines. However, with only a 60% uptake, the financial outlay has likely acted as a barrier, with not only the solar panels themselves needing purchasing, but also the electric vehicles—both industrial (e.g. electric forklifts) and on-road. The other alternative route which was found to have been taken was for Biofuel, which does not require the same financial outlay or changing of equipment as the solar option. The lack of engagement with regard to the circular practices was also evident in the findings, with only one company seeking to use the Reduce principle by recycling water within the plant and through a reduction in their use of diesel. The reduction in diesel usage is a consequence of the solar energy alternative being used.

In conclusion, this paper has demonstrated that SMEs in the UK are making efforts towards energy decarbonisation using CE principles. The results depicted that while there is a growing interest among SMEs in adopting CE practices, barriers such as financial constraints, resource shortage on decarbonisation expertise, organisational culture mismatch in CE goals and business pressure from customers and policymakers have slowed down the pace of uptake. However, there is a positive trend among SMEs in adopting readily available, stable technologies such as solar energy and biodiesel, with more financial assistance on these options. In the long term, stronger actions such as closing material loops will be necessary for SMEs to achieve sustainable operations and reduce their carbon footprint. Therefore, this study emphasises the need for SMEs to continue exploring and adopting CE practices and renewable energy options, such as solar and green vehicles, to achieve decarbonisation goals and improve their overall sustainability performance. It is essential for both policymakers and SMEs to collaborate and try and remove or reduce these barriers for CE practice adoption.

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Chapter 13
Fabrication of Porous Soft Magnets via Laser Powder Bed Fusion In-Situ Alloying

M. Biyiklioglu, Rossi Setchi, C. Guerra, P. Anderson, and M. Ryan

Abstract Today, porous magnetic materials have been one of the focal points of studies in the field of treatment due to their absorbent properties. This study focuses on the production of porous magnetic FeSi6 alloy using laser powder bed fusion (LPBF) with in-situ alloying. Water atomized Fe and Si powders with high purity were used as the starting materials. Different hatch spacing and exposure time values were investigated to examine their impact on the porosity of the structure. Cylindrical specimens were produced, and their relative densities were measured. SEM analysis and magnetic property measurements were conducted to evaluate the resulting material. The study successfully achieved the production of high-porosity magnetic material, with some control over pore formation through the laser parameters. The magnetic properties of the material demonstrated results consistent with previous studies. Furthermore, the study found that in-situ alloying in the LPBF method yields magnetic properties comparable to those obtained using pre-alloyed powder, indicating the feasibility of this approach.

13.1 Introduction

Porous materials can easily interact with atoms, molecules and ions. They can be used as adsorbent, biosensor or catalyst due to their high surface area/volume ratio [1, 2]. It finds its place in many areas from daily areas such as water treatment to bone implants [3, 4]. Pores can be formed in the material either intentionally or unintentionally during production. Stoffregen et al. catalogued them as geometrically undefined porosity (GUP) and geometrically defined lattice structure porosity (GDLSP) [5].

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Pressing and sintering methods are one of the most suitable methods to produce GUP type porous metal materials. Studies are underway to develop new materials for porous structures [6]. However, in additive manufacturing methods such as laser powder bed fusion (LPBF), GDLSP type pores can be obtained at the micron level. Likewise, depending on the area needed, porous structures can be produced from many materials such as steel, Ti alloys or ceramics [7]. One of the alloys that can be used is magnetic materials.

There are studies on the use of porous magnetic materials in rotors and transformers which prefer GDLSP type pores [8]. In another field absorbers where porous structures are used, magnetic materials have attracted the attention of researchers, especially because of their potential to purify heavy metals [9]. In these studies, traditional production methods were preferred [10].

In this study, Fe-Si alloy, which has an important place in many fields, especially in the electromotor industry, was preferred. Fe-Si alloys have high relative magnetic permeability and electric resistivity [11]. As the amount of Si in the alloy increases, the electrical resistivity increases, improving the magnetic properties. In the Fe-Si alloy containing 6.5% Si, magnetostriction reaches zero and low eddy current losses are achieved [12]. However, increasing the amount of Si significantly reduces the ductility of the material and negatively affects machinability [13]. For this reason, 3% Si alloys are preferred in industrial applications. On the other hand, studies on alloy chemistry are carried out to eliminate high brittleness [14, 15]. In addition, studies are carried out on the production of alloys with higher Si content by using additive production methods.

In pioneering studies on the production of Fe-Si alloys by the LPBF method, it was possible to produce high-density, crack-free parts [8, 16, 17]. By choosing this material, on which detailed research has been made, it is aimed to examine the findings in detail by comparing them with other studies.

The LPBF method chosen as the production method is one of the main additive production methods. With this method, both GUP and GDLSP type pores can be produced. By changing the production parameters such as laser power, laser speed, hatch spacing, GUP type pores can be obtained by providing partial melting. Also, GDLSP type pores can be obtained by pre-designing the desired spaces in the geometric design. In this study, it is aimed to produce GUP type pores in order to imitate natural pores of absorbent structures such as sponges.

The powders used in the LPBF method are generally pre-alloyed powders. However, the production of alloy powders is an important factor that increases both cost and energy consumption [18]. For this reason, researchers are working on in-situ alloying during production using blended pure element powders. Thus, it is aimed to produce alloys on a much wider scale while reducing cost and energy consumption. Hence, in-situ alloying was preferred in this study.

This study investigates whether geometrically undefined porous structures can be produced by the LPBF method with reduced total energy consumption by using a soft magnetic Fe-Si alloy.

13.2 Materials and Method

The water-atomized Fe (GoodFellow brand) and Si (Alfa Aesar brand) powders used are 99% and 99.99% pure, respectively. Dimensional analyses of the powders were performed on a Malvern Mastersizer 3000. XRD analysis was performed on a PANalytical X'Pert Pro diffractometer using a Ni-filtered CuKα radiation source operating at 40 kV and 40 mA. Diffraction patterns were recorded between 10 and 80° 2θ at a step size of 0.0167°using a back filled sample holder. Fe and Si powders were mixed in the Turbula T2C mixer at 64 rpm for 2 h. This blended powder was used in laser powder bed fusion.

LPBF was carried out using the Renishaw AM250. This machine uses an ytterbium fiber laser with a wavelength of 1071 µm, and the laser focal size is fixed at 75 µm. Point distance indicates the distance between two adjacent melting points and is set at 65 µm so that the melting spots partially overlap and that the melt can maintain its integrity. The laser power was chosen at 150 W, which is lower than previous studies [17]. It was aimed at limiting the melting and thus obtaining porosity. The layer thickness was determined as 50 µm, since 90% of the FeSi6 blended powder was below 51.5 µm. Stripe was used as the layer scanning pattern and the interlayer scanning angle is 67° as shown in Fig. 13.1.

Three different hatch spacing values, 60, 75 and 90 µm, and three different exposure time values, 53, 80, 107 µs were selected. Thus, the energy density applied by using different hatch spacing values and exposure times was changed and the effect of this situation on the porosity was investigated. The sample names use abbreviations h60, h75 and h90 to indicate hatch spacing values, also e53, e80 and e107 to indicate exposure times. For example, the sample called h60e53 was produced by 60 µm hatch spacing and an exposure time of 53 µs. Cylindrical specimens with a height of 12 mm and a diameter of 6 mm were produced.

Relative densities were measured by Archimedes method. SEM analyses were carried out with ZEISS 1540XB brand device. Magnetic properties were measured using the Bulk Material DC Characterization system developed in-house.

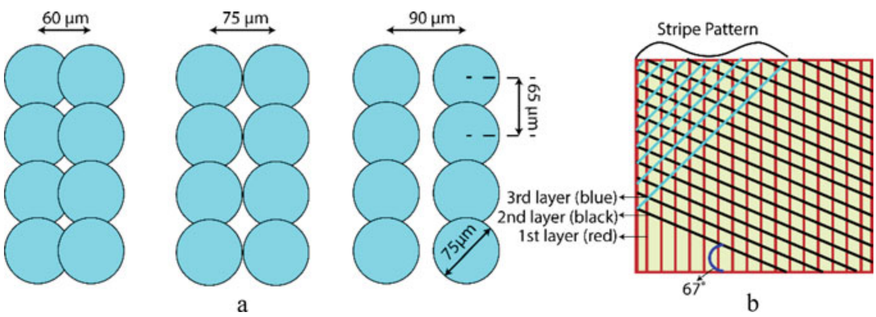

Fig. 13.1 Scanning strategies: **a** hatch spacing values, **b** scan pattern and angle between layers

13.3 Results and Discussion

Figure 13.2 shows the XRD graphs, powder characterizations and SEM images of Fe, Si and blended FeSi6 powders. Since Fe powder is produced by the water atomization method, the powder shape is irregular and the Dv50 value is 39.6 µm as shown in Fig. 13.2b. Silicon powder, on the other hand, is in the form of flakes and is very prone to clumping. This was observed both in the SEM images and confirmed by the bimodal particle size distribution, as shown in Fig. 13.2a. The Dv50 value of the silicon powder was measured as 161 µm. During the 6-h blending using a turbula mixer, these large clumped pieces were dispersed. This is thought to be due to the fact that the more rigid Fe particles act as grinding balls and break up the agglomerated silicon powders. As seen in Fig. 13.2c, small silicon particles adhered to the iron particles and mixed homogeneously. The Dv50 and Dv90 values of the FeSi6 blended powder obtained were 27.3 µm and 51.5 µm, respectively. In addition, due to the high volumetric amount of silicon powder, the amount of particles below 10 µm was high during the analysis and caused bimodal distribution. While iron powders XRD peaks matched with ferrite [19], silicons XRD peaks show a polycristalline structure [20]. As shown in Fig. 13.2c, since alloying does not occur during the blending process, the peaks of both Fe and Si elements are evident in the blended powder.

Figure 13.3 shows the relative densities of the samples produced, measured by the Archimedes method, are given. The most basic finding is that the relative density increases as the applied energy density increases when the laser exposure time is increased, or the hatch space is decreased. As seen in the graph, the h90e80 sample appears to have a higher relative density than expected. This is most likely due to the powder morphology. The flowability and packaging ability of spherical powders is the highest [21]. However, the powders used in this study are not spherical, but irregular. This reduces their flowability and packaging ability and causes extra spaces in the build table during production. In this case, it seems that the h90e80 sample does not actually have a high relative density, while the h75e80 and h90e107 samples have a low relative density. Likewise, the relative density of the h60e107 sample, which has 33% more exposure time, is almost the same as that of the h60e53. In this case, it is seen that the applied energy density is not the only factor on the pores, and the powder morphology is more effective on the pores than the applied energy density, especially at relative densities above 80%.

The effect of hatch spacing and exposure time values on the magnetic properties of the samples produced in the B-H diagrams is shown in Fig. 13.4. As can be seen in Fig. 13.4, the magnetic saturation of the material increases as the hatch spacing value decreases. Likewise, it is seen that magnetic saturation increases with the increase in exposure time. These two cases show that increasing relative density as a result of increasing the applied energy density leads to an increase in magnetic saturation. On the other hand, neither hatch spacing, nor exposure time parameters had a significant effect on coercivity. The reason for this is that coercivity is affected by the grain size rather than the relative density of the material [22]. In general, since partial melting

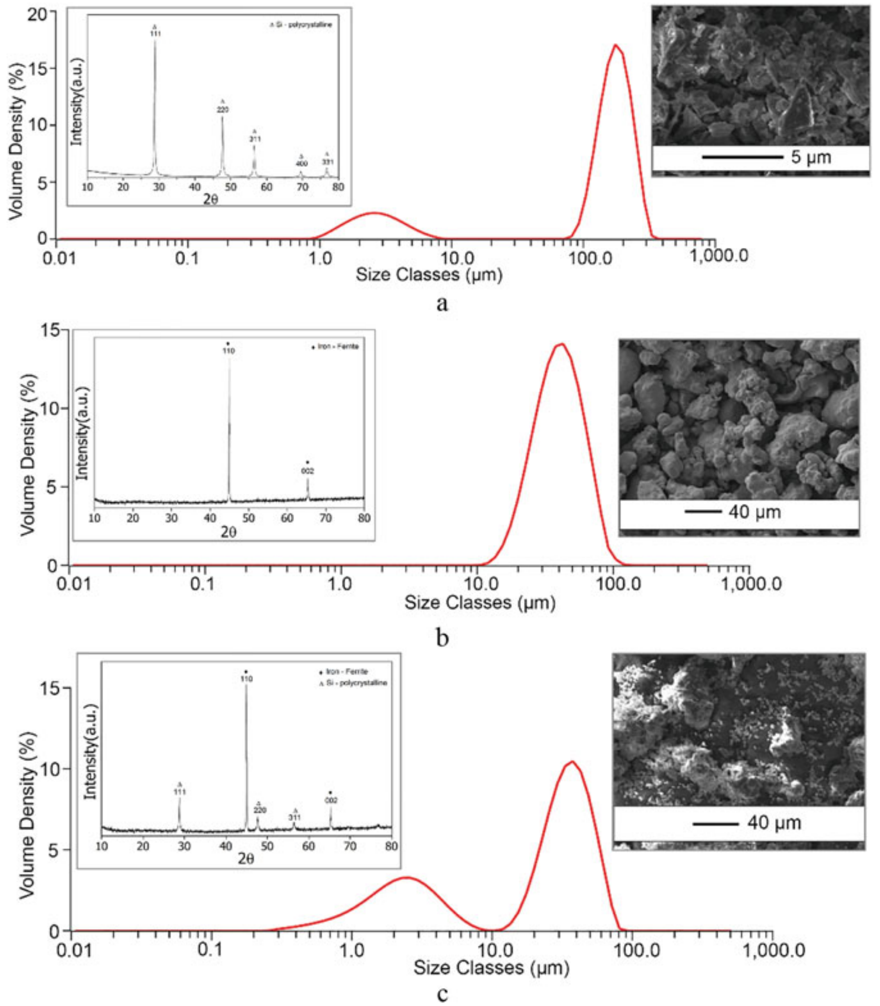

Fig. 13.2 Particle size analyzes of powders **a** Si, **b** Fe, **c** $FeSi_6$ blended

is carried out during the production process of the samples, it is expected that the grain structure obtained in this context will show similarity in the samples.

The highest magnetic saturation value obtained in this study belongs to the h60e107 sample, which has the highest density with 1.09 T, as seen in Fig. 13.5. Cramer et al., on the other hand, reached a value of 1.8 T in FeSi6 sample, which has a relative density of 99%, using the binder jet method with pre-alloyed powder. An important factor in the low magnetic saturation value obtained in this study is the high impurity ratio of the powder used. Although there is a positive correlation between intensity and magnetic saturation, it is difficult to say that this correlation

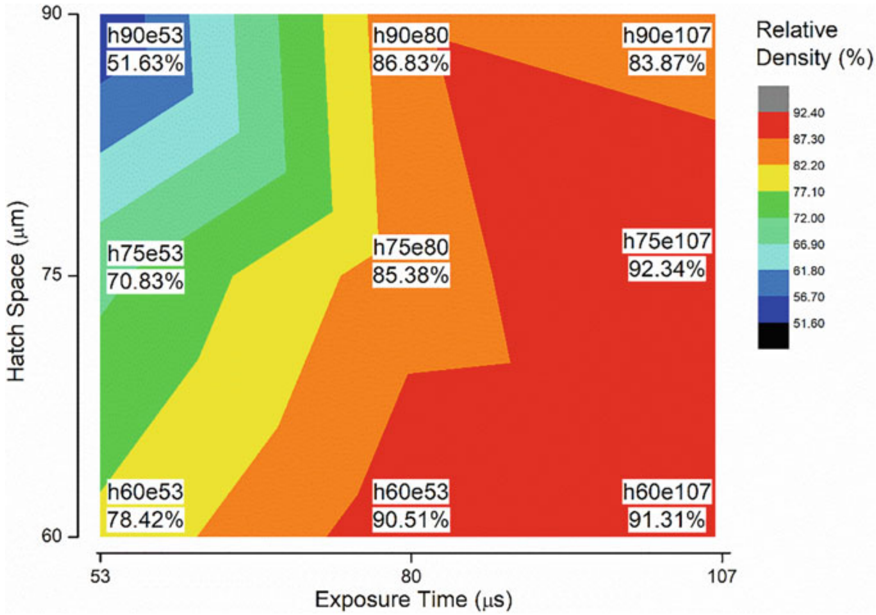

Fig. 13.3 Effect of hatch spacing and exposure time on relative density

shows a linear trend. This is particularly evident when Figs. 13.5 and 13.3 are examined comparatively. The h90e80 sample, which is approximately 10% denser than the h60e53 sample, has the same magnetic saturation value. The reason for this situation cannot be explained according to the available data. Finally, when the magnetic saturation (T) values are compared proportionally with the relative density (RD) values, the h90e53 sample has the highest T/RD value of 1.22. This value is 1.8 for Cramer samples which means porosity causes more magnetic saturation loss than anticipated.

SEM images of h75e80 samples produced using LPBF are given in Fig. 13.6. As described in Sect. 13.2, in order to obtain a porous structure, laser power and exposure time were kept lower than the studies in the literature. The low energy applied prevented laser melting from being continuous and caused macropores in the structure. Although the pores are randomly distributed, it is thought to show continuity within the structure. As shown highlighted in red in Fig. 13.6 Partial melting (1) and balling (2) were observed in all samples due to the low energy density during the laser melting process.

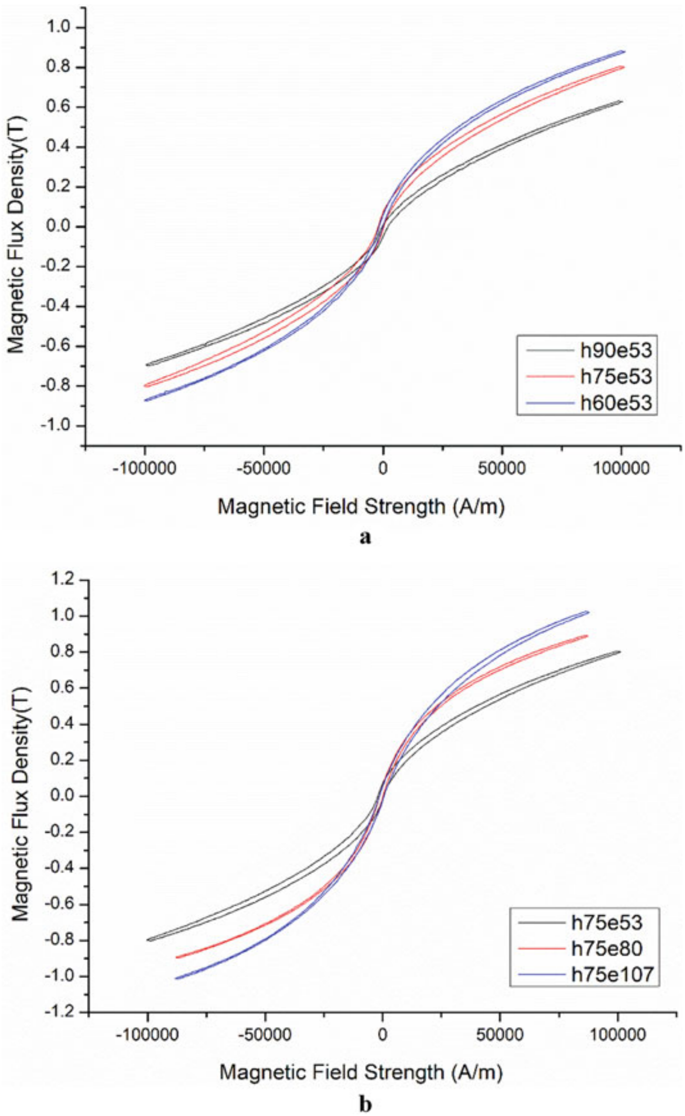

Fig. 13.4 B (T)–H (A/m) diagrams of FeSi6 samples: **a** constant exposure time (53 μs) with different hatch spacings, **b** different exposure time with constant hatch spacing (75 μm)

13.4 Conclusion and Future Works

The magnetic material with high porosity, which is the main aim of this study, has been successfully produced. Control over the porosity density was partially achieved through the hatch spacing and exposure time parameters. The magnetic saturation

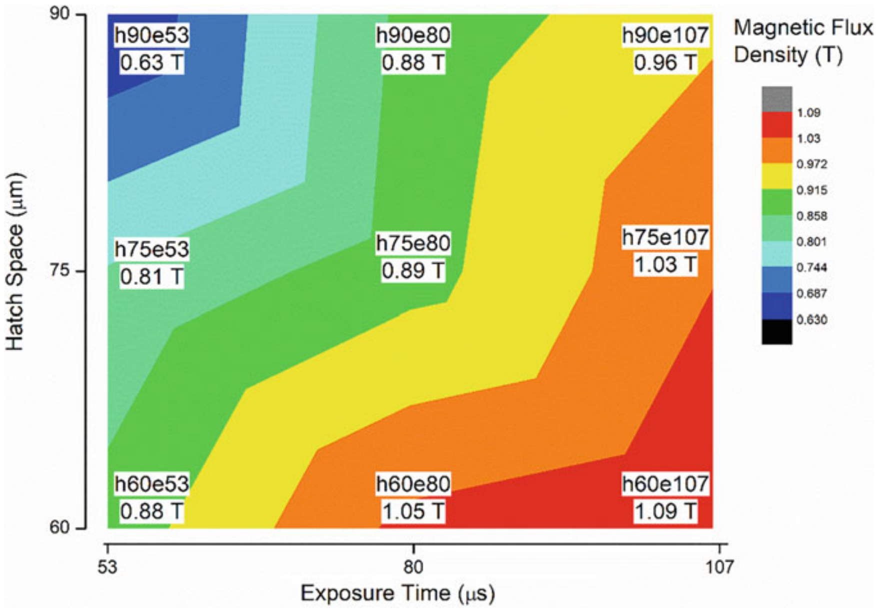

Fig. 13.5 Effect of hatch spacing and exposure time on magnetic flux density

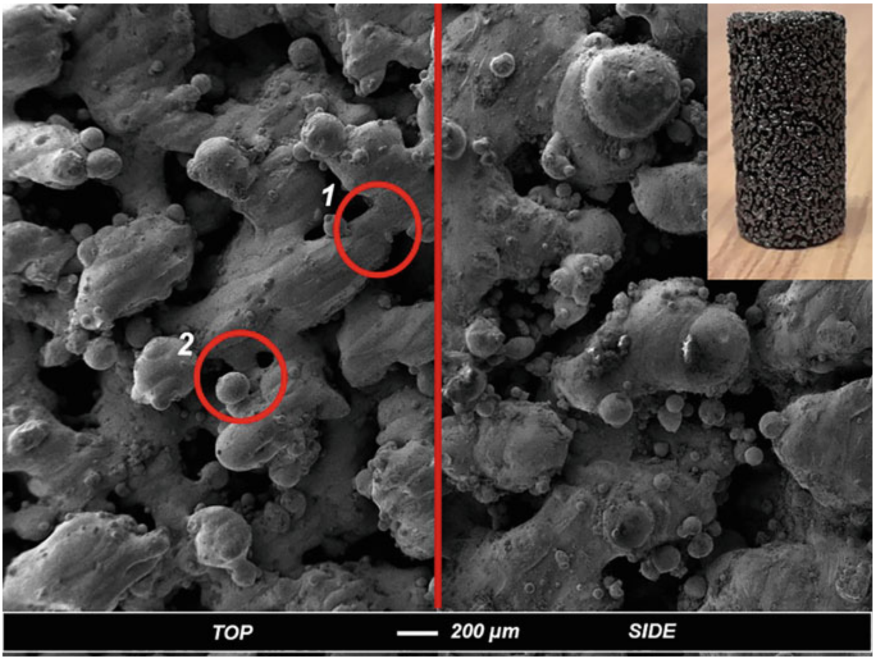

Fig. 13.6 SEM images of top and side view of h75e80 sample and photo of the h75e80 sample

values of the obtained magnetic material gave results in agreement with other studies. The highest magnetic saturation value obtained belongs to the h60e107 sample with 1.09 T. Although the pores are homogeneous and continuous in structure, they have an irregular shape. However, the direct effects of changing the hatch spacing or exposure time value on the size and shape of the pores have not been clearly determined. Finally, the magnetic properties obtained by in-situ alloying are close to the magnetic properties obtained using pre-alloyed powder. Thus, it is seen that there is no harm in using the in-situ alloying method in the LPBF method. Two drawbacks that should be considered for this study are that the powder shape is more effective than expected during the LPBF process and the impurities in the alloy powder used seriously affect the magnetic properties.

In the continuation of the study, it is aimed to create controlled pores or to produce a model with a highly porous structure by optimizing the LPBF parameters. In addition, comparative experiments will be carried out on water treatment, which is one of the potential usage areas.

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Chapter 14
Finding a Greener, Cost-Effective and Colour-Based Partial or Complete Replacement to White Portland Cement for Cast Stone Production Using TOPSIS

Devanshu Mudgal, Emanuele Pagone, and Konstantinos Salonitis

Abstract As per recent research, the use of White Portland Cement (WPC) in the production of cast stone results in significant carbon emissions. This study aims to identify alternatives to WPC that have lower carbon emissions and are cost-effective. A literature review was performed, and data were gathered on WPC and its alternatives. Based on the literature review, five alternatives were identified. An investigation was conducted to determine the most suitable replacement for WPC based on four criteria. Automatically weighted TOPSIS which is a Multi-Criteria Decision Analysis (MCDA) was used to identify the optimal substitute for WPC. The results of the analysis were used to make a final recommendation. Overall, this study provides valuable insights into the potential substitutes for WPC in the production of cast stone, which could help to reduce carbon emissions and promote greater sustainability in the construction industry.

14.1 Introduction

Cement is the most manufactured product on the earth in the twenty-first century by mass and it is the second highest consumed after water. Cement is used in all the major architectural construction works such as bridges, dams, skyscrapers and roads [1]. Cement is also a binding agent for cast stone. There are different types of cement such as Ordinary Portland Cement (OPC), Low Heat cement, rapid hardening cement and White Portland Cement (WPC) which are used based on the requirements [2]. Portland cement is the most used type of cement, and it is produced by combining clinker with gypsum [1]. To create the clinker, limestone and specific silicate aggregates are burned at a temperature just above 1500 °C in a rotary kiln [1]. As highlighted by

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Mudgal et al., WPC is an important raw material for cast stone production [3]. The white colour of WPC comes from low iron content (less than 0.5%) [3]. Due to the white colour, adding different dyes to the cement and matching the colour of the cast stone based on the customer's requirement is easier. However, such an advantage comes with high greenhouse gas emissions. The Portland cement industry is also one of the major contributors to global warming. The overall cement industry is responsible for overall 8% of global CO_2 emissions [4]. The chemical process to manufacture cement occurs at a high temperature [5]. To reach such high temperatures, fossil fuel is burned, hence emitting CO_2 and other greenhouse gases. Thus, it is necessary to find other eco-friendly and cost-effective replacements for the WPC.

WPC is used as a binding agent in concrete to build a variety of architectural features. Similarly, it is also used in cast stone which is a manufactured stone and resembles natural carved stone [4]. It is a mixture of sand, WPC, admixtures and limestone in a fixed proportion to replicate the natural stone [4]. Various garden ornaments and architectural features are made from cast stone. This paper mainly focuses on identifying a replacement for WPC using MCDA. The replacement should have lower embodied carbon and should be cost-effective when compared to WPC. The alternative of WPC then can be used in cast stone manufacturing hence reducing the environmental impact of the cast stone.

Fly Ash (FA) is a well-known alternative available for the partial replacement of the WPC. FA is the by-product of burning pulverised coal, due to that reason it is also known as pulverised fuel ash [5]. When FA is combined with lime and water, it has the similar characteristic and strength of the WPC [5]. A study performed by Khankhaje et al. found the optimum substitution level of FA with cement was between 10 and 30% [6]. The experimental outcome from this study showed that the FA showed higher abrasion resistance and lower drying shrinkage compared to concrete with 100% Portland cement. It was concluded from the study that the partial replacement of cement is beneficial for the environment [6]. The UK government is actively endorsing a reduction in coal consumption to tackle greenhouse gas emissions which make the procurement of bulk quantities of FA harder in the UK [7, 8]. FA can still be obtained from municipally incinerated waste. However, the cost of FA makes it commercially unviable for small businesses.

Another alternative that was available in the literature is called Surkhi which is a brick powder that provided strength to the dams constructed in 1895 before the popularity of Portland cement in India [9]. When Surkhi is mixed with the limestone in a set proportion, it acts as a binding agent [10]. Khan et al., have performed studies where the workability of Surkhi has been discussed in a concrete mix as a replacement for Portland cement. The experiment showed that by using 10% of Surkhi as a replacement for Portland cement, a strength of up to 35 N/mm^2 can be achieved. Since it is a brick powder, the colour of Surkhi is red [9, 10]. Also, this binding agent is produced in small quantities in India and high import costs will make it unviable for a small business.

The first complete replacement of WPC could be Belite-rich Portland Cement (BRC). BRC and WPC have similar clinker mineral composition and both of them are silicate cements however, BRC has a grey colour [11]. The grey colour of BRC resembles the OPC. Furthermore, the firing process of BRC and WPC differ as well. BRC has a higher C_2S content and lower C_3S content which is less than 35% as compared to the OPC [12]. Therefore, the BRC produces low heat during the curing process. As per Tongbo Sui et al., BRC can reduce carbon emissions by 20% compared to OPC [13]. However, due to lower heat generation, the BRC gains its strength slower than any other Portland cement [13].

Xuan et al. have mentioned in their study about Limestone calcined cement (LC3) which is a new composite cement consisting of limestone, clay and cement [12]. This composite cement uses limestone and calcined clay as supplementary materials and increases economic efficiency while also reducing the environmental impact [8]. The mechanical properties of LC3 are similar to those of Portland cement and it is highly durable. Based on the calcined clay, the colour of the LC3 varies from grey to different shades of red. When mixed with limestone, it gives a shade of bath colour [14]. In a study performed by da Silva et al., it was found that LC3 reduces carbon emissions by 50% compared to Portland cement [15].

Ground granulated blast-furnace slag (GGBS) is added to the cement to reduce the environmental impact as well as improve the strength of the concrete. GGBS is obtained as the result of quenching molten iron and steel slag. GGBS is a latent hydraulic binder forming calcium silicate hydrates after water is added. As per Sakai et al., it is more efficient than the fly ash [16]. It was also discovered in the study, that GGBS can reduce the carbon emissions between a range of 50–90% [16]. GGBS is off-white in colour [17]. Even though GGBS is an ideal partial replacement for the cement, it lacks adequate supply due to the constantly shrinking steel and iron industry in the UK [18].

The last alternative is Magnesium-based cement. In this type of cement, magnesium is combined with carbonate, phosphate, silicate-hydrate and oxysalt. Even though Magnesium-based cement is 60–90% greener compared to the PC, the higher cost of production reduces the chances of complete replacement of the PC [19]. Furthermore, due to the low pH value within the cement, it reacts with the steel reinforcement which withholds this cement to be used within large structures with steel reinforcement.

All the alternatives to cement have been listed above. However, it is hard to select one alternative as there are so many criteria such as cost-effectiveness, environmental credentials as well as mechanical properties of the material. To select the best alternative to the WPC, a methodology is required. A Multi-Decision Criteria Analysis (MCDA) can be employed to achieve this aim. MCDA methods such as VIKOR (VIekriterijumsko KOmpromisno Rangiranje) have been used in studies to evaluate cement manufacturing methods [20]. Similarly, two-phase MCDA methods which include AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) approach to rank different types of high-performance concrete mixes based on the workability, strength and durability [21]. Similarly, in the metal casting industry, TOPSIS has been used numerous times. For example, in selecting the material for the hydro-turbine [22]. However, none of the studies have ranked different types of cement based on their technical, environmental and financial criteria. In cast stone, the colour of the final product is non-trivial. The ingredients within the mix affect the overall colour. To rank, the colour of the cement should also be included in the analysis as it will affect the overall decision about selecting the alternative. None of the studies included colour in their decision criteria as it was not an important criterion. This study uses automatically weighted high-resolution mapping of multi-criteria decision TOPSIS analysis developed by Pagone et al. to find the complete or partial replacement of the WPC for cast stone [23]. TOPSIS is an ideal method for this study as it is reliable and provides rationality. The automatically weighted method requires no interference from the decision-maker hence providing the result without any external influence [23]. More about this method is explained in the next section.

14.2 Methodology

Automatically weighted MCDA TOPSIS is used within this study as it integrates with this methodology. By finding a business-viable alternative to cement, the overall carbon dioxide emission of cast stone can be reduced. The methodology used in this paper is covered into three parts as shown in Fig. 14.1.

14.2.1 *Choosing Alternatives, Data Collection and Data Preparation*

In this step of the methodology, a literature review is performed where different replacements are identified. The properties of the material are divided into technical, environmental and financial criteria. These criteria are further divided into sub-criteria. So, the technical criteria have hydration, strength and colour families as the sub-criteria. Whereas the cost comes under financial criteria. Similarly, carbon dioxide emission is a sub-criterion of the environment. All the data on these criteria have been collected during the literature review. It is important to arrange the data in a specific format. The format is shown in Table 14.1.

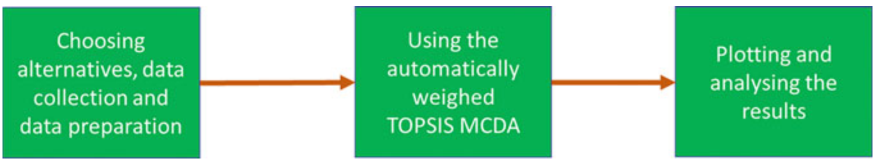

Fig. 14.1 Methodology

Table 14.1 The alternatives of WPC arranged for automatically weighted MCDA

Sub-criteria	Impact	Category	White Portland Cement	Ferrite cement	Belite-rich Portland Cement	GGBS	Calcined kaolinitic cement	Magnesium based cement
Cost	–	Financial	6	19.14	10.96	3.25	5.23	4.03
Carbon dioxide Emission	–	Environmental	652.2	435.4	497.6	155.5	491.38	186.6
Cube strength	+	Technical	20.4	25	54.7	64.2	36.6	83
Hydration	–	Technical	28	7	34	28	7	28
Colour	+	Technical	5	1	1	1	5	1

14.2.2 Using the Automatically Weighted TOPSIS MCDA

The automatically weighted method is developed by Pagone et al., and the working of this method has been explained in detail in the study published by the author [23]. This technique covers all the scenarios giving each sub-criteria priority in all four laws, i.e. “First two”, “Halving”, “Quadratic” and “Uniform” [23]. The input data is arranged in the format as shown in Table 14.1. Usually, a spreadsheet is used and the data is saved in ‘.csv’ format. The file goes into the software that performs four sets of analyses. They are mapped based on the combinatorial ranking of categories [23]. The four analyses are:

1. Uniform: In this case, each criterion is given equal weightage.
2. Halving: As the name suggests, the weight is halved at the next position in the ranking.
3. Quadratic: A furthermore aggressive reduction in the ranking according to quadratic expression is mentioned by Pagone et al. [23].
4. First two: The distribution of the weight is governed by the first two categories.

The importance of each criterion is dictated by the initial letter of the relevant criteria. For example, on the x-axis of the “first two” chart, if labelled “fte” where ‘f’ stands for finance, ‘t’ stands for technical and ‘e’ stands for environmental. In such case, finance has the priority followed by technical and environmental. The impact category does not ask the decision-maker for any input other than the ‘ + ’ or ‘−’ sign. So for example, the bigger the value, the better it is for the sub-criteria 1 and 4 which fall under Criteria 1 and 2. Similarly, with the ‘-’ sign, the lower the value, the better it is for the sub-criteria 2 and 4. However, no weightage is required from the decision-makers [24].

14.2.3 Plotting and Analysing the Results

As a result of running the Automatically Weighted TOPSIS MCDA, the alternatives are ranked accordingly. The output of this method comes in ‘.csv’ file format and the number of output files depends on the number of alternatives as each scenario is covered. These graphs cover all the possible scenarios giving each sub-criteria priority in all four laws, i.e. “First two”, “Halving”, “Quadratic” and “Uniform”. The results can be plotted graphically to view easily and for better interpretation.

14.3 Case Study

The above-mentioned methodology was applied to a cast stone manufacturing company in Northamptonshire, United Kingdom. The company produces cast stone in different colours such as Bath, Terracotta, Slate, white and Portland. The products of this company were divided into product families based on their colour. The colours of each alternative have been mentioned in the literature review. They represent the number of options a cast stone can be produced in if an alternative cement is used. For example, a slate colour cast stone can easily be produced using a grey cement alternative, i.e. Belite-rich Portland Cement. However, Belite-rich cement cannot produce any other colour other than slate. For this case study WPC has been included to have a better comparison of the current and future state.

14.3.1 Choosing Alternatives, Data Collection and Data Preparation

As the first step of the methodology, the alternatives are identified which are mentioned below through a literature review. The three criteria chosen are Financial, Environmental and Technical. The sub-criteria are cost, carbon emission, cube strength, hydration and colour family. All the alternatives to WPC are shown in Table 14.1.

14.3.2 Using the Automatically Weighted TOPSIS MCDA

The data has been arranged ready for the automatically weighted MCDA as shown in the table below. The table is input as a.csv file.

14.4 Result

14.4.1 Uniform Distribution

In this category, the weight has been uniformly distributed in all the categories. As shown in the Fig. 14.2a, GGBS is the winner cement alternative followed by the Magnesium-based cement. Ferrite cement is the least desired alternative. Currently, the company uses WPC, which holds the fourth rank in the uniform distribution. A further close analysis of the cement can be seen in the next section where the cement is ranked based on combinatorial ranking.

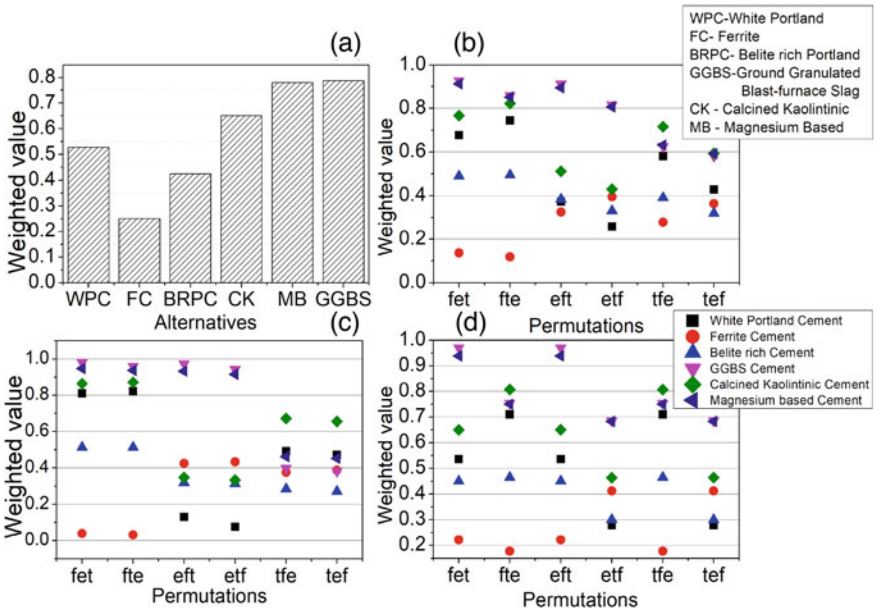

Fig. 14.2 Ranking of each alternative with weight distribution for **a** uniform, **b** halving, **c** quadratic and **d** first two. The first letter of x-axis denotes three criteria, i.e. F: Financial, E: Environmental and T: Technical

Combinatorial Ranking of Categories by Importance: Halving, Quadratic and First Two.

As explained in Sect. 14.2.2, the order of importance for categories is determined by the position of the first letter of the corresponding category in the identifier on the x-axis. Figure 14.2b shows the "Halving" category where the weightage is halved. In "Halving", GGBS cement has the highest score in four categories, i.e. 'fet', 'fte', 'eft' and 'etf'. When technical criterion is given importance, Calcined kaolinitic cement has the highest score. The overall second-best performer in this category is Magnesium-based cement. The lowest score was from Ferrite cement for categories 'fet', 'fte', eft' and 'tfe'. For 'etf' was WPC.

In case of "quadratic", as it is shown in Fig. 14.2c, GGBS has the highest score except in 'tfe' and 'tef' where technical category is given importance. In those two categories, Calcined kaolinitic cement has ranked the highest. Ferrite cement ranked lowest when financial criteria is given importance. In terms of environmental criteria, WPC has scored lowest. Belite rich cement scored lowest when technical criterion is given importance.

"First two" shows similar results to "Quadratic" and "Halving". As shown in Fig. 14.2d, in "First two" GGBS has the highest score except for 'tfe' 'fte' and 'tfe'. Ferrite cement is the lowest performer in 'fet', 'fte', 'eft' and 'tfe' whereas, WPC is lowest performer in 'etf' and 'tef'.

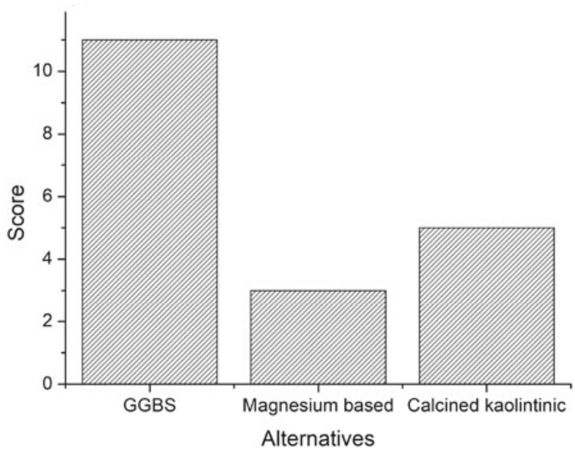

Fig. 14.3 Overall ranking of alternatives based on occurrence as the best option in each category

The most common alternative from all the cases that has resulted in ranking the best option is shown in Fig. 14.3. According to the ranking, GGBS is ranked highest followed by Calcined kaolinitic and Magnesium-based cement.

14.5 Conclusion

In this study, five alternatives of White Portland Cement were identified that can be used as binding agent in cast stone. The aim was to find an alternative that is greener, cost-effective as well as stronger compared to the White Portland Cement. The high carbon dioxide emissions of the WPC are the driving factors behind this study.

The mechanical properties, cost and environmental impact of each alternative were used to select the best alternative. To select the alternative, automatically weighting TOPSIS MCDA method was employed. Five alternatives have been found through the literature review and presented in this study. White Portland Cement has also been included in the study which is currently being used in cast stone production. Each alternative was divided into three criteria, i.e. environmental, financial and technical. As per the results, GGBS cement can be an excellent alternative to the WPC. Being the cheapest cement, it has the lowest carbon emissions of 155.5 kg/ton. However, GGBS has two limitations. First, the colour of cement produced by GGBs is not suitable for cast stone production. As cast stone is made in different colours currently, it can only be used in grey if GGBS is used for cast stone production. Secondly, it is hard to achieve a reliable supply of GGBS cement in the UK market for mass production of goods. Similarly, the other two options, i.e. Magnesium-based and Calcined kaolinitic cement, are not available for mass production either, making the currently used White Portland Cement the most suitable cement to be used in cast stone commercially.

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Chapter 15
Influence of Laser Speed and Power on the Magnetic Properties of Fe-50 Wt% Ni Alloy Manufactured by LPBF

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Abstract Soft magnetic materials are used in a wide range of devices, including mobile phones, computers, motors, and inductors. Among the soft magnets, the Fe-50 wt% Ni alloy exhibits superior properties such as high magnetic saturation and permeability with low coercivity, when manufactured by conventional methods such as injection moulding. However, until now, it is not clear if modern manufacturing methods such as those based on laser powder bed fusion can affect the magnetic response. This work aims to determine experimentally the influence of laser speed and power through additive manufacture and subsequent magnetic characterization of the manufactured samples. These measurements were compared with those of a commercial sample obtained via conventional fabrication methods. The results show that it is possible to achieve magnetic saturation similar to the commercial samples, with both values of ~1.7 T and acceptable permeability of 66 $A \cdot m^{-1}$ compared to the commercial ones 159 $A \cdot m^{-1}$ if samples were fabricated with 190 W laser power and 300 $m \cdot s^{-1}$ laser speed.

15.1 Introduction

Soft magnetic materials, such as Fe–Si, Fe–Ni, Fe–Al–Si, and Fe–Co to name some, are widely used in modern electric and electronic devices [1, 2]. They transform electrical to mechanical energy and are indispensable in applications that involve the conversion of the electric current waveform. Therefore, their application includes transformers, inductors, communication equipment such as audio transformers,

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recording heads and magnetic modulators and are widely used in ordinary appliances such as hair dryers, vacuum cleaners, washing machines, air conditioners, phone (wireless) chargers, and computer power supplies [3].

A soft magnetic material is characterized by very high magnetic permeability, low coercivity, and high magnetic saturation [4]. In practice, it is visualized on a hysteresis loop where the magnetic response shows a quasi-reversible ferromagnetic system of dipoles, whose response is nonlinear and depends on the dipoles' rotation into the field direction applied [5]. The Fe-50% Ni alloy, also called permalloy, is considered a soft magnet with a relatively high magnetic saturation (~1.6 T), high relative permeability (10,000–55,000), and low eddy current losses [5, 6]. Although it has advantages from the point of view of magnetic properties over other alloys, it is more expensive than Fe-Si.

Currently, soft magnets are fabricated through a cold rolled strip process, and in the case of brittle alloys or hard-to-work, the manufacturing process could be powder injection moulding or powder metallurgy [7, 8]. However, these techniques are limited in terms of the shape of the part that can be produced and therefore the customization of the magnets. For this reason, additive manufacturing (AM) has been suggested as an alternative for producing parts with magnetic properties [7]. Fe-50% Ni alloy has been successfully manufactured by laser powder bed fusion (LPBF) [9, 10] as well as through direct energy deposition (DED) [11, 12]. The authors have demonstrated reaching lower magnetic saturation and permeability than the alloy fabricated by other techniques, due to the presence of porosity and other defects produced during the solidification. Nevertheless, it has been observed that by increasing the grain size and applying stress relief through heat treatment, magnetic properties, such as permeability, can be enhanced in samples fabricated using AM [13]. Haftlang et al. conducted a study on Fe–Ni alloy, investigating how its crystallographic texture can facilitate the alignment of magnetic domains, thereby capitalizing on crystallographic anisotropy [12]. Additionally, Zhang et al. who produce Fe-30% Ni by LPBF discuss the laser parameters handling to achieve low crystallite size (130 μm) and then get better magnetic properties [14]. However, the influence of important process parameters such as the laser speed and power on the magnetic properties is currently unknown.

This study aims to fabricate samples using an experimental design to statistically analyse the optimal combination of laser parameters to achieve optimum magnetic properties. The results are compared with the magnetic properties of samples obtained through conventional methods, to assess the feasibility of replacing them with additive manufacturing. The novelty of this work is in developing a new understanding of the laser parameters that positively impact the laser powder bed fusion of magnetic components made of Fe-50 wt% Ni alloy.

15.2 Methodology

15.2.1 Sample Fabrication

Commercial Fe-50 wt% Ni alloyed powders were purchased, which were fabricated using Nitrogen atomization, with a particle size < 30 μm. Cylindrical samples were fabricated and built on a stainless steel construction platform, using laser powder bed fusion (Concept Laser Mlab 200R Ge) under a nitrogen atmosphere. The samples were fabricated using a 200 W fibre laser with a spot size of ~75 μm varying the volumetric energy density (VED). Additionally, a meander scanning pattern was employed with a 67° rotation between the consecutive layers. The samples were cylinders of 8 mm in height and 6.4 mm in diameter following ASTM E9 [15]. As shown in Table 15.1, the fabrication followed the design of the experiment (DOE) with variables laser power (P) and laser speed (V), both on three levels, producing each variable set in triplicates. The layer thickness and hatching space were set to 30 μm and 70 μm, respectively. After the fabrication, the as-built samples (AB) were removed from the stainless steel platform using wire electric discharge machining (W-EDM), applying a constant voltage of 100 V and a current of 2.5 A, respectively.

Additionally, an 8 mm in diameter and 50 cm in length Fe-50 wt% Ni bar (abbreviated AR—as-received) was purchased, which was cut with an abrasive disc to produce samples of 6 mm in height.

Table 15.1 Samples fabricated through additive manufacturing and obtained from conventional technology (wrought)

ID	P (W)	L (μm)	V (mm·s^{-1})	H (μm)	VED (J·mm^{-3})
AB S1	180	30	300	70	285.7
AB S2	180	30	400	70	214.3
AB S3	180	30	500	70	171.4
AB S4	190	30	300	70	301.6
AB S5	190	30	400	70	226.2
AB S6	190	30	500	70	181.0
AB S7	200	30	300	70	317.5
AB S8	200	30	400	70	238.1
AB S9	200	30	500	70	190.5
AR	As received or commercial sample				

15.2.2 Microstructural and Density Characterization

The metallographic specimens were prepared by wet grinding using sandpaper from #400 to #4000 grit and then polished with colloidal silica suspension. The microstructure was revealed using an aqua regia, composed of 15 ml HCL and 5 ml HNO_3, for 10 s. The surface images were produced with a scanning electron microscope (SEM) ZEISS 1540XB. The density was measured with the Archimedes method, whose values varied from 8.09 to 8.13 g·cm^{-3}, reaching 98% of relative density.

The phase composition was determined by X-ray diffraction (XRD) using an X'Pert3 MRD XL and equipped with Cu Kα1 radiation source ($\lambda = 1.54056$ Å). The accelerating voltage and current were 40 kV and 40 mA, with a scan rate of 0.02°·s^{-1} in a scan range of 20–80°. The phases were identified using X'pert, and then, the Rietveld refinement was performed using MAUD software.

15.2.3 Magnetic Characterization

Next, the saturation magnetization taken at 80,000 A·m^{-1}(B_{80k}) and peak permeability (μ_r) of commercial and additively manufactured cylindrical samples were measured. The magnetizing current was provided by a bespoke hysteresis graph developed at Cardiff University [16] incorporating a Kepco bipolar DC power supply Lakeshore Gaussmeter and Fluxmeter, and a PC running a custom-designed LabVIEW virtual instrument. The sample was wound with a 10-turn coil and magnetized to a peak magnetic field strength of 80 kA·m^{-1} with a cycle time of approximately 5 min.

15.3 Results and Discussions

15.3.1 Morphological Characteristics

Figure 15.1 shows the Fe-50 wt% Ni powder alloy SEM image and its particle size distribution. The particles are mainly spherical, where the bigger particles have some satellites of small diameter, while the rest of the powder is composed of a large number of small particles. The histogram exhibits a log-normal distribution, where 90% of the particles are under 30 μm and many particles are about 5 μm in diameter.

Figure 15.2 shows the SEM image of an as-built sample, taken from the top surface, and its diffraction pattern. The SEM image shows the micrograph of the alloy whose grains are randomly oriented and with grain size distribution due to the fabrication method [17]. The zoom image shows the grain boundary and the structure of fine dendrites inside of the equiaxed grains observed commonly in metallic alloys

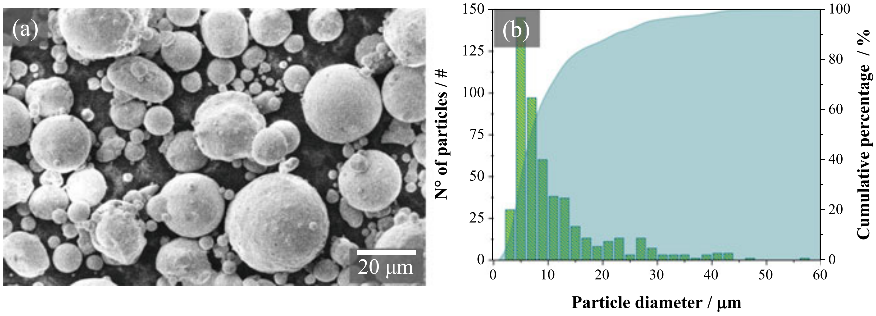

Fig. 15.1 **a** SEM image of alloying powders and **b** histogram of particle size distribution

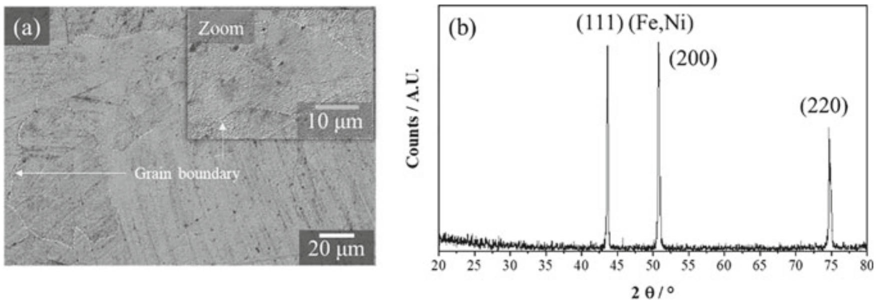

Fig. 15.2 **a** SEM image of AB sample surface and **b** the X-ray sample diffraction pattern collected with Cu Kα radiation

fabricated through AM [18, 19]. It is important to note that small pores (approximately 5 µm) were observed in both the top view and cross-section. However, the density reached was on average 98.4% ± 0.5% as measured by the Archimedes principle.

The diffraction pattern shows peaks associated with the γ-FCC (face-centred cubic) structure with a space group Fm–3 m composed of Fe and Ni atoms. According to the Rietveld refinement, the cubic cell has a lattice parameter of 3.588 Å and suggests texture oriented in (200). F. Haftlang et al. [12] researched the Fe-50% Ni fabricated through direct energy deposition (DED) and the influence of the crystallographic orientation-dependent magnetic properties. They found that maximization of magnetic properties could be done when the grains are oriented on Cube {001} <100> [5].

15.3.2 Magnetic Properties

Figure 15.3 compares the complete hysteresis loops (B–H curves) and zoom of AR and some AB samples. The loops are typical of soft magnet materials, where the AR sample reaches saturation under a small external magnetic strength, reflecting high permeability (μ_r) characteristics. In fact, all AB samples exhibited lower permeability than AR samples due to the internal defects generated by LPBF, which hindered magnetic domain alignment at the same magnetic force applied. However, the magnetic saturation at 80,000 A·m^{-1} ($B_{80\,K}$) was similar between the AR and AB samples whose values were 1.71 ± 0.03 T for AR and a range of 1.56 ± 0.12 T to 1.73 ± 0.09 T for AB. It demonstrated that AB can reach similar values regarding magnetic saturation, whose values seem to depend on the alloy rather than other factors. Table 15.2 shows the principal data extracted from the hysteresis loop.

Similar values have been reported for magnetic saturation [4, 8, 20] but with other fabrication techniques with permeabilities over 40,000 [12]. However, samples fabricated through AM can reach a permeability of 5,000 with a coercivity (H_c) of 100 A·m^{-1} [9] and a magnetic saturation of 1 T [11]. Nonetheless, the AB samples move in a wide range of H_c from 1,730.5 ± 173.8 to 455.5 ± 158.7 A·m^{-1} It is due to the presence of sample's internal defects as porous, voids, residual stress, dislocation density and impurities [4, 19, 21] that impact negatively the magnetic properties. These internal defects are often part of the metallic samples manufactured by AM, which are characterized by having an average of 2% porosity when considered fully dense and the residual stress left by local heating and rapid solidification. Therefore,

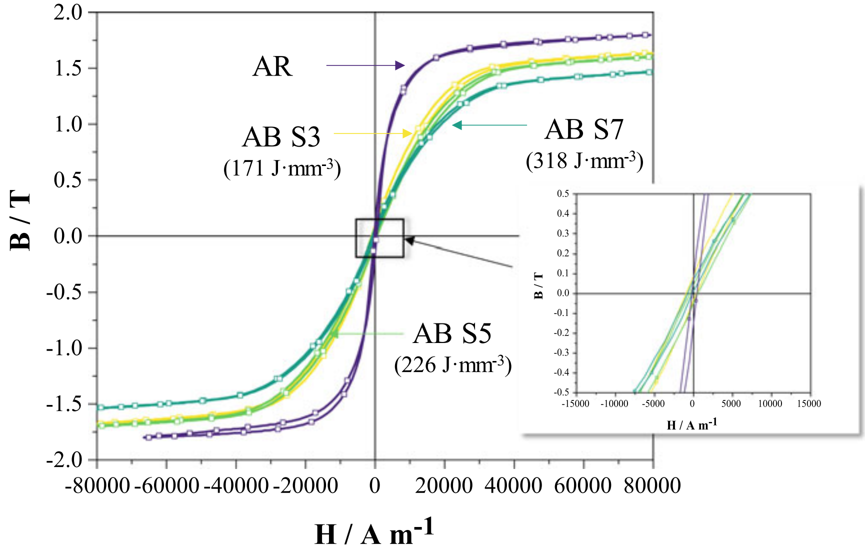

Fig. 15.3 Magnetic hysteresis plot (*B*–*H* curves) of the magnetic field strength (*H*) and flux density (*B*) of AR and selected AB samples

Table 15.2 Magnetic field saturation, permeability, and coercivity of the as-built and as-received samples

ID	$B_{80\,k}$ (T)	μ_r (-)	H_c (A·m^{-1})
AB S1	1.64 ± 0.02	66.3 ± 0.1	455.5 ± 158.7
AB S2	1.72 ± 0.10	64.4 ± 19.3	1,730.5 ± 173.8
AB S3	1.63 ± 0.01	64.5 ± 1.4	1,390.9 ± 96.3
AB S4	1.73 ± 0.09	62.5 ± 0.1	1,092.1 ± 108.8
AB S5	1.63 ± 0.00	64.3 ± 6.1	978.9 ± 86.3
AB S6	1.63 ± 0.00	59.8 ± 0.7	555.3 ± 447.7
AB S7	1.56 ± 0.12	56.5 ± 3.9	797.6 ± 315.1
AB S8	1.64 ± 0.02	61.2 ± 4.7	965.6 ± 187.6
AB S9	1.64 ± 0.02	56.5 ± 8.1	993.9 ± 55.0
AR	1.71 ± 0.03	159.3 ± 41.2	558.9 ± 106.0

it is expected to achieve lower magnetic properties. However, studies have demonstrated that heat treatments that increase the grain size and allow residual stress relief could improve the magnetic properties of samples fabricated by AM [22, 23].

Figure 15.4 uses a contour graph to show the influences of the laser parameters (power and scan speed) on the magnetic properties such as the magnetic "saturation" ($B_{80\,k}$), the permeability (μ_r), and coercivity (H). The results show that the combination of low laser power and speed is possible to achieve the maximum B_{80k} and μ_r and the lowest coercivity. The latter phenomenon can be attributed to the low laser speed, which enables the melting of the layers while concentrating the power in smaller increments.

Figure 15.5 shows a scatter matrix that combines the magnetic characteristics and the laser parameters utilized in the construction of the samples, providing statistical evidence of their correlation using the Pearson coefficient (r). The VED is strongly influenced by the laser speed (V) rather than the laser power (P) since as the speed increases VED drops drastically. The matrix reveals an inverse relationship between P and μ_r, suggesting that excessive melting of the layers may lead to an increase in microstructural defects. As V increases, there is a corresponding increase in the

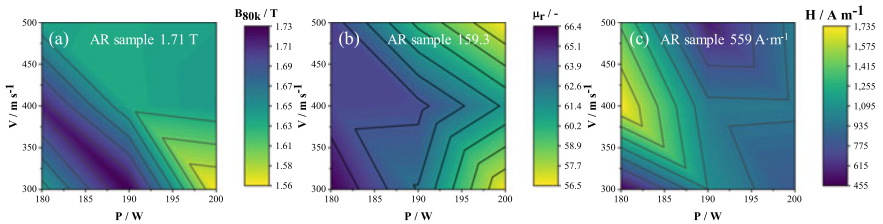

Fig. 15.4 Contour plot of the **a** magnetic field (B) collected at 80 k A·m^{-1}, **b** permeability (μ_r), and **c** coercivity (H) influenced by laser power (P) and scanning speed (V)

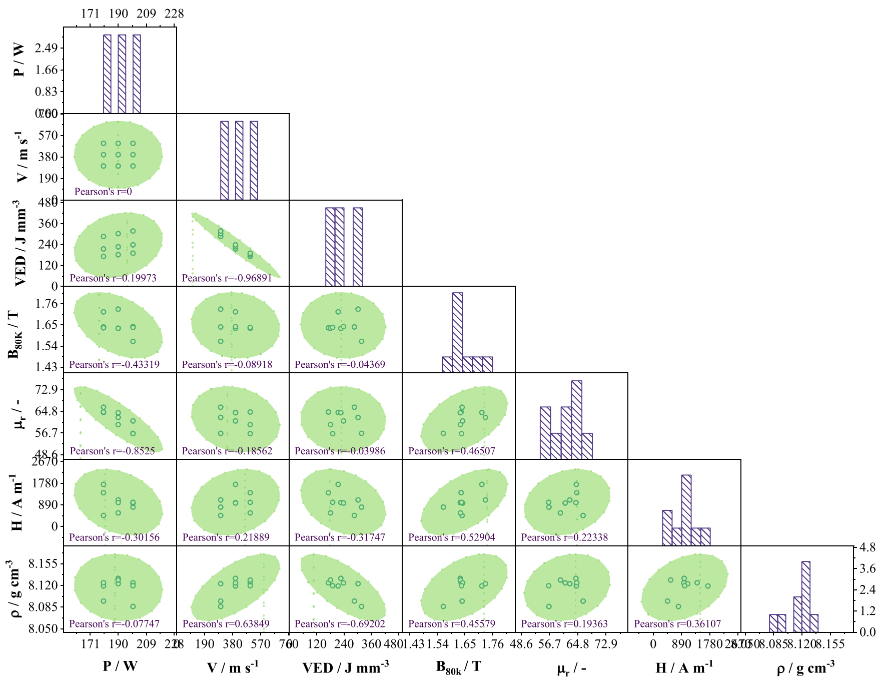

Fig. 15.5 Scatter matrix to visualize bivariate relationships between combinations of laser power and speed, volumetric energy density (VED), sample density (ρ), and magnetic properties

sample density (ρ), which suggests that some magnetic properties can be attributed to the presence of porosity. This is evident in the case of B_{80k} and H, which exhibit a slight positive correlation with density.

15.4 Conclusions

The comparison of the magnetic properties of samples manufactured conventionally and by LPBF, when varying the laser power and speed, indicates the following:

- The B_{80k} achieved for samples produced by LPBF was close to the commercial samples. This means that the magnetic saturation was somewhat unaffected by the type of manufacturing method employed.
- The μ_r is greater in AR samples than AB due to the presence of many internal defects in the last, since this acts as a pinning mechanism for magnetic domain walls. This opens the opportunity to explore the effect of annealing to decrease or eliminate some of these defects to improve the magnetic properties.

- The laser speed affects the volumetric energy, used to construct the AB samples, more than the laser power. Therefore, V influences the permeability, where at higher laser speed, the permeability decreases due to the appearance of more internal defects as porosity.
- The best magnetic properties obtained using AM were achieved using a laser power of 190 W and a low speed of about 300 $m \cdot s^{-1}$, with total volumetric energy close to 300 $J \cdot mm^{-3}$.
- The alloy produced through LPBF exhibits magnetic properties that are comparable to those of the same alloy obtained through conventional methods. Therefore, further research is needed to explore the potential of laser powder bed fusion and to manufacture Fe–Ni components.

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Chapter 16
Examining “the Jungle” of Metrics Available to Improve Sustainability Performance of Energy Intensive Industries

Juan Ramon Candia and Peter Ball

Abstract Energy use in manufacturing is under increasing scrutiny given challenges, especially in recent times in Europe, for the cost and security of supply. In addition, the carbon impact of energy must be reduced dramatically in the coming decade(s) to meet national legally binding targets and alignment with global net zero objectives. This is being acutely felt in the energy intensive or “foundation industries” that are high energy users with disproportionally high carbon impact due to the higher use of non-renewable sources. Metrics and associated targets implicitly drive a focus on energy efficiency, however, a wider set of metrics that better represent sustainability issues could be used to foster broader solutions both within companies acting alone as well as collaborative solutions by working across organizations whether commercial or not for profit. This paper examines the spectrum of potential metrics to drive better sustainability performance (and greater resource efficiency, including energy efficiency) in the pursuit of broader societal goals such as the UN’s Global Goals. The paper reports on metrics research at multiple scales from process to factory to system levels. The findings show how alignment with emerging potentially mandated standards could lead to broader innovation in manufacturing.

16.1 Introduction

Energy intensive industries (e.g. glass, food, paper, chemicals, ceramics, metals and cement) account for nearly 80% of manufacturing greenhouse gas (GHG) emissions and primary energy use [1]. Termed “foundation industries” in the UK (including metals, glass, paper, ceramics, cement and bulk chemicals) [2], they are exposed to significant energy insecurity and cost pressures and are implicitly major carbon emitters. Significant and rapid changes are required at scale to reduce their impact

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and meet national and global carbon targets in the coming decade(s). The main routes for the energy sector to achieve net zero targets are well known: electrification of end-use sectors; CO_2 capture, utilization and storage, including removal of CO_2 from the atmosphere; the use of low-carbon hydrogen and hydrogen-based fuels; and the use of bioenergy. But these require a strong and targeted R&D effort in these net zero technologies [3]. Efficiency gains, using best available technologies at scale, developing new solutions, and, where further improvements or substitutions are not possible, collaborating to share resources are also relevant routes for significant carbon reduction.

Organizations are increasingly required to measure and communicate their non-financial performance to demonstrate their achievement of sustainability goals. There are several sustainability reporting frameworks and tools aiming to help (or demand) organizations communicate social, economic and environmental performance to stakeholders. Measuring sustainability of organization is driven by dual objectives. Firstly, it is essential from the management perspective in order to improve production process decision-making, e.g. increase efficiency, reduce water and energy consumption, reduce the use of inputs and maximize outputs, reduce waste generation, etc. Secondly, the increasing market pressure (regulations, competitiveness, information transparency) coupled with the awareness of the consequences of organizations' activities, demand that their sustainability credentials are also reported to both internal and external stakeholders, e.g. customers, suppliers, local community, government, Non-Governmental Organizations (NGOs), shareholders, investors, rating agencies, among others.

With this aim, frameworks, tools, standards and guidelines have been developed to help organizations to measure, assess, report and disclose aspects of sustainability performance. The UK TransFIRe project is focused on the pursuit of Net Zero in the foundation industries by transferring best practice (applying "Gentani", the minimum possible resources needed), creating new materials and processes and working with communities. Through its different Work Streams (WS), the TransFIRe project is identifying the most suitable metrics for the Foundation Industry (FI), by looking at different levels for measuring and reporting performance, i.e. looking into specific manufacturing process Key Performance Indicators (KPIs), to multiple process levels and factory level, and beyond the factory. A particular gap in research and challenge for practice is to identify and deploy metrics that align with current and emerging global sustainability reporting standards whilst operationally driving fundamental improvements at scale internally and collaboratively. Addressing metric alignment challenge will contribute to literature and in turn foster the value of resource use and avoid value being missed or destroyed.

The paper first identifies appropriate metrics at multiple scales to drive fundamental improvement in sustainability reporting and energy efficiency through examination of literature. Next, a focus on the macro scale, factory and "system" levels and alignment is introduced. System is used here in preference to supply chain so to capture activities and opportunities beyond the immediate supply chain, including communities. Findings suggest that by using broad factory level metrics and aligning with emerging global standards at system level, there is potential to drive net reductions both through absolute reductions in the factory as well as exploiting reuse opportunities with other local businesses or the public community. Following this, challenges in applications are discussed before conclusions which are drawn and future research opportunities are teased out.

16.2 Literature Review

Continuing on from the literature exploration in the introduction, this section highlights the key sources that were utilized. Literature from practitioner literature and peer-reviewed literature is drawn from. Prominent journals including Cleaner Production and Sustainability were searched for sustainability, energy and the supporting metrics, tools, methodologies and frameworks. This section brings out general references prior to the deeper documentation of the literature in the next section.

Firstly, sustainability reporting is an essential tool for organizations to demonstrate accountability to their stakeholders [4]. Firms need to report their sustainability credentials (i.e. adequate information on organizations’ social, economic and environmental performance) to the wider society given the increased market pressures, rising awareness of society, increased environmental and social challenges, easy access to information and need for transparency. The Global Reporting Initiative (GRI) defines sustainability performance reporting as “the method of assessing, disclosing, and being accountable to external and internal stakeholders regarding how businesses contribute to sustainable development goals (SDGs)” [5]. However, the current process through which organizations communicate their sustainability performance to stakeholders is questionable and remains a significant concern [5].

Secondly, comparing and evaluating organizations’ sustainability-related performance is not possible due to the absence of widely accepted standards for sustainability reporting [6]. This is in line with other authors [e.g. 7] who argue that organizations need to identify and communicate both quantitative and qualitative key performance indicators in order to show the degree of achievement of the SDGs. All standards emphasize transparent and complete sustainability performance reporting. Furthermore, sustainability reporting is not a magic tool that can simultaneously fulfil communication and management functions [8]. Additionally, it must support the disclosure of corporate climate risk “as well as on the strategies and actions implemented to mitigate the effects of climate change and adapt to them, in order to inform investors, shareholders, customers, suppliers, society and other stakeholders” [9, p. 2].

Thirdly, support for reporting is needed. According to the United Nations Research Institute for Sustainable Development (UNRISD), measuring the sustainability performance of companies and organizations (in other words, their positive and negative impacts on resources that are vital for the well-being of the planet) has been an extremely complex endeavour. Even though the significant progress in sustainability measurement and disclosure over the past years and decades, current indicators, methodologies and reporting models “still fail to provide an adequate basis for assessing impacts related to socio-economic, governance and environmental dimensions of sustainable development” [4]. Over the last two decades, several sustainability performance measurement systems as well as sustainability assessment tools have been developed by various organizations. Despite this, and even recognizing the importance to measure and assess sustainability performance, stakeholders seem dissatisfied with the current status [10].

Finally, with specific reference to the Foundation Industries (FIs), and as it could be expected, there are no widely adopted tools or frameworks to measure their sustainability performance. For example, for chemical industries, the most relevant FI sector in the UK by turnover [11], and more specifically in the pulp and paper, the Emergy Accounting method (EMA) is very appropriate for the evaluation of “the efficiency, effectiveness and sustainability of the papermaking process under different perspectives (resource quality, fossil energy and material consumption, environmental and human-driven support)” [12, p. 313]. When it comes to the cement manufacturing, the ecological footprint is shown as a useful tool, although of limited value when used as stand-alone indicator. EMA is shown again as a useful complementary indicator, as it may provide quantitative metrics of the level of industrial sustainability. Carbon footprint is also mentioned as a useful indicator for this type of industry [13].

In summary, the key findings from the literature review were: (a) Whilst firms are engaging in improvements, there is a challenge on how to translate these operational improvements into improvements using metrics provided by upcoming standards, (b) multiple standards are emerging which make consistent reporting challenging and (c) there is a lack of tools and methods to support companies in creating the metric values.

This research therefore seeks to address the aforementioned sustainability reporting gaps by asking: “How can different levels of sustainability metrics aid companies drive performance whilst aligning to sustainability reporting standards”. The significance of this is enabling organizations to ensure operational improvement and monitoring and external reporting are efficiently linked and easily open to audit.

16.3 Methodology

The research used a broad literature review as a starting point. This included peer-reviewed literature, standards that are established or emerging and practitioner literature to capture latest practice. The search included metrics concerned with the factory, supply chain or system, had scope covering efficiency or Rs strategies (reduce, reuse, recycle) and covered broad resource use. Excluded were works at machine tool/technology levels, focused on only one pillar of sustainability (economic, environmental, social) or outside manufacturing scope (e.g. healthcare).

Next the literature was collated and clustered by application scope. Top-level clusters of process level, factory level and supply chain/system level formed, and these were further categorized. The researchers mapped composite metrics for factory level and competing but overlapping metrics based on existing and emerging standards at system level. To understand which are the most valuable sustainability reporting frameworks for FIs for the system level, a mapping of the main tools and frameworks was carried out, describing their scope, objectives, legal context, pros and cons.

Two stages of review have been carried out. The first stage used the academic workstream groups for refinement to ensure that the assembled metrics frameworks were representative of the broad scope of the published evidence found. The participants were academics (spectrum of professorial grades). The refinement reviewed consistency and any ambiguity in categorizing the frameworks, e.g. the claimed life-cycle stages covered. The second stage of review was to consult practitioners working in the energy intensive industries for completeness, applicability, current application and emerging application. The feedback served to validate the mapping.

A third stage of review is currently underway therefore not reported here. This is the use of workshops to understand the challenges with applying system level metrics. The following questions are being posed: How much data do you collect? What do you report on today? What would you need to comply with these standards? How much would it cost? Are these useful to measure progress/performance? Can you see a trajectory of change? How should we prioritize these reporting tools?

16.4 Results

The TransFIRe project has been analysing sustainability metrics in the FIs from different perspectives. Through its different work streams, it has been looking at different levels for measuring and reporting performance, ranging from the process level, to factory level, to the “beyond the fence” level, i.e. we can look at this from a specific production line or a unit process, a multi-process system, a facility level, to the system view, adding the perspective of external stakeholders, including the surrounding community and the environment. Figure 16.1 provides a schematic representation of the three levels. Each of the levels will be detailed in the subsections that follow. It is worth mentioning that this scheme is an oversimplification of group of metrics, as these levels may not always have clear-cut boundaries. For example, by measuring performance of a firm at the factory level (Level 2) by using a circularity approach, we are effectively also starting to move towards a systemic view of their performance (Level 3).

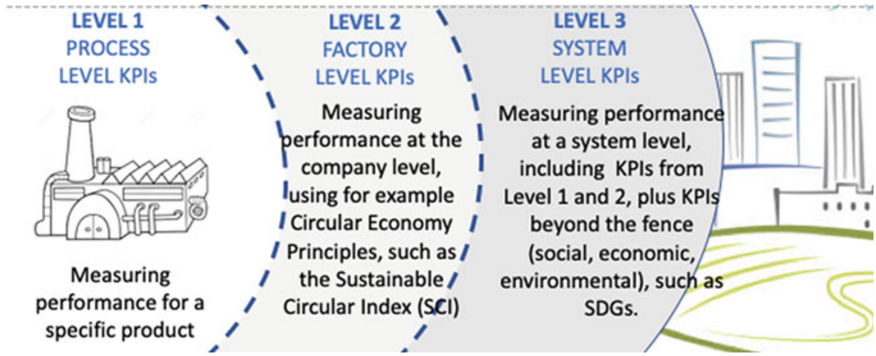

Fig. 16.1 Schematic representation of the three levels for grouping sustainability metrics

16.4.1 Process Scale Metrics

A framework has been created for the manufacturing industries to identify the right environmental KPIs. It includes building a database for environmental KPIs, categorizing, ranking and composing a final KPI set for specified targets. The developed method allows the most effective KPI to be selected for specified targets as well as identifying unmonitored environmental aspects. The framework has been corroborated by subject matter and industry experts, in which the potential benefits have been verified [14].

16.4.2 Sustainability Performance Indicators at a Factory Level

A broad range of tools available for measuring industry performance within the factory's limits was investigated. A literature search to obtain tools and frameworks that incorporated performance measurement included keywords of circularity, circular economy, lifecycle, sustainability and performance. The analysed tools were selected on inclusion of the three pillars of sustainability (economic, environment, social) and use at nano, micro and meso levels. Initially, 17 methods were reviewed, see Table 16.1, targeting sectors such as: Biotech, Pharmaceutical, Automotive, Electrical, Waste, Gypsum, Steel, Textile, Plastic, Chemical, Coal and Construction. After initial analysis, five methods were selected as appropriate for further evaluation based on their lifecycle scope. Specifically, the tools must address more than one lifecycle stage, must recognize influence on external activity, must account for downstream activity and have evidence of practical applicability. These tools are given in Table 16.2, indicating the target sectors as well as the main core principles being addressed regarding lifecycle theories.

Table 16.1 Potential methods for sustainability performance indicators

Methods	
1. CE Building Scale	10. Material Reutilization Score (MRS)
2. Expanded Zero Waste Practice Model (EZWP)	11. Circular Economy Index (CEI)
3. Product Recovery Multi-Criteria Decision Tool (PR-MCDT)	12. Circular Business Model Set of Indicators based on Sustainability (CBM-IS)
4. Mathematical Model to Assess Sustainable Design and End-of-life Options (SDEO)	13. Comprehensive Evaluation Index System (CEIS)
5. Multi-Criteria Evaluation Method of Product-Level Circularity Strategies (MCEM-PLCS)	14. Value-based Resource Efficiency Indicator (VRE)
6. Sustainable Circular Index (SCI)	15. Evaluation Index System (EIS)
7. Set of Indicators to Assess Sustainability (SIAS)	16. End of Life Best Practice Indicators (BPI)
8. Sustainability Performance Indicators (SPI)	17. Reuse Potential Indicator
9. Systems Indicators for Circular Economy Dashboard (SICED)	

Table 16.2 Summary of the five assessment tools selected for measuring company performance

Tool	Level	Industry	Method	Life cycle	Authors	Journal
Sustainable circular index (SCI)	Micro		Quantitative	R2 R4 R5	Azevedo et al. 2017	Resources
End of life best practice indicators (BPI)	Nano	Gypsum	Quantitative	R3 R4	2016 Jimenez-Rivero, Garcia-Navarro	Waste biomass valorisation
Circular business model set of indicators on sustainability (CBM-IS)	Nano Micro	Textile, plastic Electrical	Quantitative Qualitative	Full life cycle	Rossi et al. 2020	Cleaner production
Value-based resource efficiency indicator (VRE)	Micro	Various	Quantitative	R1 R2 R3 R5	Di Maio et al. 2017	Resources, conservation and recycling
CE building scale	Micro	Construction	Likert	R1 R2 R3	Nuñez-Cacho et al. 2018	sustainability

Legend: R1 reduce; R2 reuse; R3 recycle; R4 recover; R5 remanufacture; R6 redesign

These indicators could support managers in assessing their level of sustainability and circularity and could help them implement operational practices to improve their companies' performance on these two areas. They could also represent a benchmarking tool for manufacturing companies to assess their sustainable and circular behaviour [15].

16.4.3 Sustainability Reporting Frameworks Beyond the Fence

As has been mentioned, there are many standards, methodologies and tools for assessing, tracking and communicating sustainability performance. These include: metrics and KPIs, aspects of governance, risk management, targets and transparency issues. These frameworks can support both companies' disclosures and investment processes, by specifying a structure, definitions, metrics and methodologies. However, these existing frameworks are typically applied only on a voluntary basis, and the market has not converged on a single framework [16].

Examples of initiatives, standards, frameworks, and organisations, include (but are not limited to): Carbon Disclosure Project (CDP), Dow Jones Sustainability Index (DJSI), Global Reporting Initiative (GRI), Sustainability Accounting Standards Board (SASB), Global Real State Sustainability Benchmark (GRESB), Taskforce on Climate-Related Financial Disclosure (TCFD), Sustainable Development Goals (SDGs), Science-based Targets (SBT), Science-based Targets Initiative (SBTi), Greenhouse Gas Protocol, EU Taxonomy, Corporate Sustainability Reporting Directive (CSRD), Transition Plan Taskforce (TPT) and Sustainable Development Performance Indicators (SDPI), among many others.

In October 2021, the UK Government published the Greening Finance Roadmap, signalling that it intends to strengthen new and existing sustainability reporting requirements for companies, including publication of climate transition plans [17]. Companies are increasingly aware of exposure to climate-related risks and opportunities. In response, many companies and financial institutions have defined climate-related targets and now need to develop strategies for delivering on their objectives, whilst at the same time addressing their identified risks and opportunities [18].

Further, the UK has set itself ambitious and legally binding targets to cut greenhouse gas (GHG) emissions to net zero by 2050, with binding interim targets. It pledged at UN climate negotiations to cut emissions by at least 68% by 2030 and at COP26, the UK committed to work towards becoming the world's first net zero aligned financial centre and ensuring that financial flows shift towards supporting a net zero economy.

16.4.4 Examples of Emerging Initiatives for Sustainability Reporting

Below a brief description of three of the main frameworks under development to assess and disclose on sustainability-related matters:

The Transition Plan Taskforce (TPT). The Transition Plan Taskforce (TPT) will make recommendations to inform the UK's regulatory requirements on transition plan disclosures. Launched in 2022 to develop a gold standard for transition, it encourages entities to back up their targets with rigorous and credible short-term actions. The Transition Plans must comply with three principles: ambition, action and accountability. According to [19], over 80% of listed companies in the UK say they are committed to becoming net zero by 2050, but 95% of them have not yet disclosed transition plans.

Prototype of Climate-related Financial Disclosure Standard. In 2020, a group of sustainability standard setters—CDP, the Climate Disclosure Standards Board (CDSB), the Global Reporting Initiative (GRI), the International Integrated Reporting Council (IIRC) and the Sustainability Accounting Standards Board (SASB), referred as the "the Alliance"—published a prototype climate-related financial disclosure standard. Its objective is to accelerate convergence in global sustainability reporting standards, building on the "well-established work" of both the TCFD and the Alliance. The prototype outlines a shared vision that integrates both financial accounting and sustainability disclosure and builds on the TCFD recommendations. "These commitments have led users of climate-related financial disclosures—investors, lenders and insurance underwriters—to increasingly seek decision- useful information on organizations' plans and progress to move to a low-carbon economy, referred to as transition plans, including the use of associated climate-related metrics and targets to track such progress" [18].

New Rules on Corporate Sustainability Reporting in EU. The EU Corporate Sustainability Reporting Directive (CSRD) came into force in 2023. The directive modernizes and strengthens the rules about the social and environmental information that companies must report. A broader set of large companies, as well as listed SMEs, will now be required to report on sustainability, approximately 50,000 companies in total.

The new rules will ensure that investors and other stakeholders have access to the information they need to assess investment risks arising from climate change and other sustainability issues. They will also create a culture of transparency about the impact of companies on people and the environment. Finally, it is expected that reporting costs will be reduced for companies over the medium to long term by harmonizing the information to be provided. The first companies will have to apply the new rules for the first time in financial year 2024, for reports published in 2025.

16.5 Challenge of Sustainability Reporting Beyond the Fence

The review of metrics across the process, factory and system ("beyond the factory fence") levels revealed a wealth of potential metrics that companies in collaboration with broader stakeholders could use to evaluate operational impact. Factory and process level metrics are established, however, challenges remain for the energy intensive FIs.

First, based on in-depth industry interviews and literature analysis, the Enterprise Research Centre (ERC) for UK Research and Innovation (UKRI), identified many challenges: increased international competition, high energy costs, regulatory pressures to reduce emissions and environmental impacts. Sustainability metrics can drive improvements here given "we cannot manage what we do not measure". To reduce energy consumption or increase efficiency, e.g. companies need to have a monitoring system in place, identify areas for improvement (hot spots), measure progress and maintain change. Similarly, upcoming regulations (and market pressures from financial institutions, larger companies/clients in the supply chain, civic organizations) will demand firms have a formal and transparent system in place for measuring, reporting and informing about sustainability performance (including climate change pledges).

Second, when it comes to the challenge of climate change and the need to measure, report and improve companies' performance related to their carbon emissions, FIs will need to measure scope 1, 2 and 3 emissions and commit to a reduction target based on SBT. Larger FIs are starting to do this, but many SMEs are not. Areas of SME support could include: awareness raising, training and financial resources.

Third, with the development and sophistication of digital technologies and tools, service firms are offering solutions to companies to help them in this challenge. By using technologies such as Artificial Intelligence (AI) and Machine Learning (ML), they have found ways to simplify this otherwise extremely complex journey.

Fourth, specific to FIs, whilst their scope 1 and 2 impacts may dwarf scope 3, their solutions do not all reside in internal efficiency and process technology upgrade; net reduction solutions may come from collaborating with others or rethinking how to exploit all resources (including wastes) that they control. Sustainability performance frameworks with examples from FI and wider could help inspire, justify and manage change. Attempts have been made to apply more systemic frameworks, e.g. cement industry ecological footprint measurement. However, it has been concluded that this still needs to be used in combination with other indicators such as carbon footprint.

16.6 Conclusions and Future Work

In this "jungle" of tools for measuring performance, it is easy for organizations to get lost. Thus, the framework developed by Sherif et al. [14] as part of the TransFIRe project could provide a useful tool for companies as a starting point to identify the most relevant KPIs, particularly at the process level. Similarly, when looking at circular economy strategies, Foundation Industries (FIs) can start by looking at the five tools that have been prioritized. These tools provide alternatives for organizations, depending on their specific sector, aims, timing and resources.

This paper considered how can different levels of sustainability metrics aid companies drive performance whilst aligning to sustainability reporting standards, particularly for FIs. Also considered was how tools and methods could bridge the operational to external performance reporting. Potential for net reductions through opportunities beyond immediate production do exist, however, emerging tools for system level lack fidelity to support wider collaboration. Two areas for further research were identified.

First, research is needed to specify a consolidated toolset that supports both internal and external changes to practices and the resulting changes in performance. For the "beyond the fence" level, tools should be aligned with the upcoming UK, EU, North American and other country regulations, and will necessarily include aspects of: carbon emissions, carbon reduction targets, risk and opportunities derived from climate change, adaptation plans, and wider sustainability indicators.

Second, in strengthening their community relationships (in the broadest sense), the use of these tools by FIs is expected to impact positively by providing information transparency (to reinforce trust) and identifying collaboration opportunities with neighbouring firms, local organizations, local government, etc. This has the potential to drive innovations beyond immediate production transformation to encompass system level transformation that leads to net system, not just net factory, reductions. However, additional research is needed to further understand the support FIs need to effectively implement these metrics, particularly regarding the more systemic reporting needs.

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Chapter 17
Rethinking Consumer Acceptance of Circular Services and Product-Service-Systems

Minna Lammi, Maria Holgado, and Maria Antikainen

Abstract Shifting from selling products to offering them as part of a service, i.e. within a product-service system (PSS) is thought to offer viable opportunities for implementing circular economy (CE)-based business models. Yet, although adopting such a model would require changes in daily consumption practices, few studies have examined the consumer reception of novel circular offerings, a gap this article addresses. Data collected in focus groups and interviews present a range of factors that accelerate or inhibit consumer acceptance of CE services. The analysis of factors revealed missing insights in previous studies: a smooth delivery and the technical level of the product to promote acceptance, and consumer's emotional connections with certain products to hinder acceptance.

17.1 Introduction

Product-service systems (PSS) have been discussed as one way to move towards both sustainable lifestyles [1, 2] and circular businesses [3]. Developing PSS within a circular economy (CE) context is a means to incorporate externalities, such as economic, environmental and social issues associated to products' usage and end-of-life, into the business offerings and operations. Internalizing externalities supports innovations towards building sustainable business models [4]. The promise of PSS is to create environmentally sustainable alternatives for consumers on the principle that when a company owns a particular product, it has the incentive to make it as materials and cost-efficient as possible while making money via service offerings [5–7]. Zaring

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et al. [8] have stated that a service is environmentally favourable when the total amount of environmental impact prevented, as compared to an alternative, is larger than the amount of environmental impact it generates. On the other hand, as Barquet et al. [6] have pointed out, PSS business models do not in themselves guarantee sustainability; indeed, they can even have negative impact on the environment, e.g. environmental rebound effect for example due to higher consumption [9].

The aim of PSS is to provide customers with a solution instead of a product and create customer value by offering multiple product-service combinations and wide-ranging collaboration between companies [5, 10, 11]. One of the goals of this cooperation would be to establish long-standing relationships with consumers, with the aim of addressing consumers' desires to satisfy their needs and seeking solutions that are easy and affordable (e.g. [12]). The PSS literature suggests, however, that we need a better understanding of how the model creates value for customers, what consumers think about these hybrid offerings and how consumption practices can change (e.g. [12–15]). Moreover, Annarelli et al. [5] stress the importance of exploring customer acceptance of the PSS model due to its important shift in consumption mode from one focused on possession to one focused on usage.

In this article, we use the concepts of CE-based product-service systems (CE-PSS) and circular services to emphasize the circularity aspects of PSS and service offerings, respectively. We define them as those PSS offerings or service offerings that contribute to closing the loop of products or materials, cascading the use of resources and minimizing waste; therefore, contributing to the CE.

The research field is rather new and unexplored, thus, there is a knowledge gap in both research and within company practices in terms of understanding consumer acceptance of CE-PSS or circular services. Thus, the goal of this study has been to identify characteristics that increase the likelihood of consumer adoption of such solutions. Our research question is: *What are the factors promoting or hindering consumers' choosing to use novel CE-PSS and circular services*? The theoretical foundation for the study is constituted from multiple traditions including practice theories and consumer behaviour research, services from the perspective of CE research, and PSS literature, extending and complementing the various scientific traditions in order to build depth to the research. Our findings provide new empirical insight into the factors increasing the likelihood of consumer acceptance of CE solutions based on service and PSS offerings.

17.2 Research Background

The background of this paper is in two projects, both of which investigated the possibilities and consumption aspects of the circular economy. In both projects, companies were co-creating the scope and specific questions for interviews in pilots and focus groups. Our first project, AARRE, focused on user-centric business models in the circular economy, and we had five company partners representing waste management, manufacturing, logistics and retail sectors. In AARRE, the companies wanted to build a broad understanding of consumers' views and intentions and readiness to participate in the circular economy. We organized pilots with them and conducted focus groups and interviews with customers. The second project, Open Mode, focused on customer-centric supply space management and had three partner companies. In Open Mode, the companies' need for knowledge was much more specific, but we were also able to communicate the findings from AARRE project to them. The companies were all working in logistics and deliveries and were keen on understanding market possibilities and intention to use and pay for circular services.

17.2.1 Consumer Acceptance from a Theoretical Perspective

Research on CE business models and consumer acceptance has utilized several theoretical traditions of consumer research. The background of these studies has been the desire to understand the factors behind consumption and sustainable consumer behaviour. The theories can be divided into several groups [16]:

(1) Rational choice theory and its extensions rely on economics' idea of rational, calculating consumer who maximize utility and minimize costs.
(2) A theory group that is criticizing rational choice theories adds attitudes, intentions, moral and emotional aspects to consumer behaviour.
(3) Cultural theories, including consumer culture theories, are looking at consumption cycle, identity building and symbolism in consumption.
(4) Practice theories are used especially in discussions about sustainable consumption in social sciences and explaining problems in attitude-behaviour gap.

Chamacho-Otero et al. [17] found in the literature review about consumption in the CE that half of the articles used first or second theory group—most popular was theory of planned behaviour [18] from the second group. The other half of the articles relied on various third and fourth group theories [17].

We acknowledge the cultural and societal aspects of the consumer behaviour: previous research suggests that everyday practices often change slowly [19], and that when new products and services are introduced, they are often seen as risky and treated with suspicion [20]. To be able to become part of everyday life, regardless of whether they are materials, products or services, novelties need to connect with common systems of things, ideas and competencies [19]. Consumer studies have identified transformation in routines and habits as playing a key role in achieving long-lasting effects [14]. To be readily adopted by consumers, innovations must resonate with their existing practices and ongoing dynamics [19]. According to prior studies, the intention to use is often seen as a proxy for consumer acceptance but not equal to it [21, 22]. Guiot and Roux [23] have found that some consumers are driven by a desire to distance themselves from a wasteful commoditized lifestyle and see intrinsic benefits in consuming less.

17.2.2 Consumer Acceptance of PSS

There is a growing body of literature on consumer willingness to explore alternative ways of consuming products, rather than buying them. In order to gain higher customer acceptance of service-oriented solutions, however, companies need to provide attractive offers or at least the same level of function and comfort as provided by conventionally purchased products [24]. To date, the discussion of the relative advantages of various service models has focused on extended customer solutions (e.g. rather than selling customers the tools to paint their houses, a full refurbishment service might be offered), economic issues, functionality and consumer satisfaction [25].

Prior studies have listed several factors that have been found to influence consumer acceptance of PSS offerings (e.g. [26, 27]). The enabling factors from previous studies can be broadly organized in five categories: (1) product characteristics, (2) offering characteristics, (3) consumer characteristics, (4) provider characteristics and (5) perceived advantage. We have mapped the literature on both enablers and barriers to PSS against these five categories. Table 17.1 presents the overview of the factors enabling and hindering PSS acceptance. This provided the starting point for our research on the subject.

17.3 Methodology

The nature of the research—i.e. understanding consumer acceptance of circular services and PSS—motivated our decision to use a qualitative approach. We aimed to deepen the understanding of consumer acceptance in different situations and build up empirical insights into the factors that affect it. The qualitative research approach is effective in these types of studies, allowing researchers to explore novel phenomena. Hence, it does not give representative results of the whole Finnish consumer population.

In order to gain rich and versatile data, we used multiple collection methods in two research projects between 2016 and 2020. Our approach included one-to-one interviews as well as focus groups to provide opportunities for individual and collective sensemaking regarding the novel services. Consumers were presented scenarios in both ambiguous and precise terms (the latter informed by engagement with companies) and experiential opportunities within a pilot of a tool rental service. This approach provided a diverse set of materials for consumer exposure to novel understandings that could trigger forward-looking thinking and prospective sensemaking on intended users [40, 41, 42].

In the AARRE project, we gathered insights from 5 companies developing circular products and services to frame the questions for consumers and to understand the specific features of a rental service pilot. We collected data from three kinds of sources, as shown in Fig. 17.1. In the Open Mode, we gathered insights from 3

Table 17.1 Enablers and barriers to PSS adoption

Category	Enabler PSS adoption	Barrier PSS adoption
Product characteristics category concerns aspects related to product type, availability of access and payment alternatives, price and affordability	Product is expensive to buy, is used seldom [26, 27] and need-based payment is available [28, 29]	Product is used merely for their primary function without associated social or emotional value [30] Concerns about lack of availability of product information [31]
Offering characteristics category refers to elements of the PSS model or service design and delivery system	Providing convenience, ease of use, and peace-of-mind of product care [24, 25, 32]	Concerns about service reliability [32] and hygiene, health and safety aspects [28] Uncertainty on the concept, rules and intrusiveness perception of the PSS model [29, 33]
Consumer characteristics category refers to features of consumers that influence their decision to engage in a PSS model or not	Matching consumer attitudes, values and circumstances [24–26, 34]	Requiring a change in consumer habits [25] or learn new skills [12] Consumer desire to own a product [35] Lack of knowledge on product life cycle costs [36]
Provider characteristics category concerns aspects related to the consumer relationship with company providing the PSS or service	Provider has good reputation, is trusted and interactive communication channels [27, 37–39]	Concerns about the reliability of the service provider [32]
Perceived advantage category refers to the holistic perspective of how the PSS or service benefits the consumer respect to owning the product	Ability to solve multiple needs and advantages compared to alternatives acceptability [24, 25, 27]	Difficulty to compare price advantage between owning product and using services [38] Product ownership more convenient due to current societal norms [27]

companies operating or willing to operate circular services to understand the potential service features, and we then organized our fourth source of data (Fig. 17.1). All interviews and focus groups were recorded and transcribed verbatim to increase findings' reliability [43]; the audio and text files formed the research material analysed using the NVivo qualitative data analysis software programme using the codes found from literature (see Table 17.1). After the first round of analysis and first coding round, we decided to code all the different data together regardless of the data source. The results were first presented to companies; we obtained permission to publish them after the end of both projects.

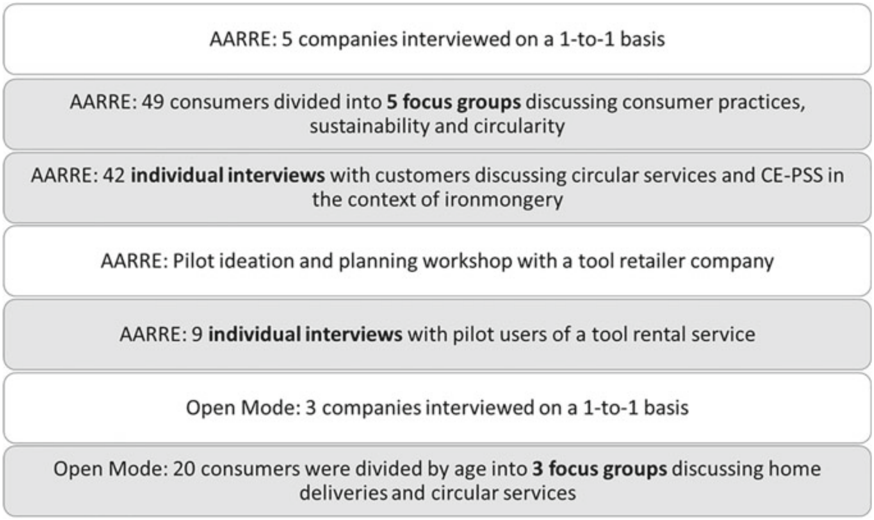

Fig. 17.1 Data collection methods

17.4 Findings and Discussion

This section organizes the research findings according to themes and categories. Table 17.2 presents the identified factors for acceptance of CE-PSS and circular services according to the five categories introduced in the background section. Moreover, the novel findings (in bold in the table) respect to PSS literature are discussed below.

Two novel factors promoting acceptance emerged which had not been covered before in the PSS acceptance literature. The first one, related to the offering characteristics category, is defined as a smooth delivery (time, place and communication style). As one respondent said: '*…ideally, it should be so that the time frame is narrowing; we agree it will come next week on Wednesday, let's say between 10–18, it's the first one, and then when they know when it's coming, then they give a narrow time frame or even a precise time.*' Our analysis shows that consumers valued convenient timing and accuracy of location in service delivery. In the context of home delivery, the acceptable time frame was around two hours and customers also recognized the worth of being able to track a delivery in real time. Furthermore, consumers valued delivery apps that had functions where you can follow the delivery van: respondents mentioned that they used these functions also like games with children waiting the delivery to arrive. '*…you were able to follow the delivery van on the map… my son was sitting with the phone in his hand following the van, soon it was home and then he ran towards the parking lot… it is great entertainment* [*for kids*].'

The second one, within the product characteristics category, concerns the technical level of the product. A major benefit of buying services instead of owning goods is that there is no need for arranging or conducting maintenance. This is also linked

Table 17.2 Identified factors in consumer acceptance of CE-PSS and circular services

Category	Factors promoting acceptance	Factors hindering acceptance
Product characteristics	High price of product purchase High variable cost or total life cycle cost of purchased product Infrequent use of products	**Characteristics of the product lead to emotional investment**
Offering characteristics	Convenience (incl. saving storage, maintenance time), practicality, flexibility **Smooth delivery (time, place and communication style)** Quality and reliability of the offering (i.e. product and service)	Poor accessibility of product/service Problem of availability at need Safety concerns (hygiene) Uncertainties (risks, fear of misuse, insurance, costs and responsibility)
Consumer characteristics	Willingness to change and experiment Need for flexibility because of current life situation	Habits as an obstacle to acceptance; unfamiliarity of the concept Desire to own; emotional vs. practical considerations **A strong relationship with products, linked to personal identity** Anxiety about intrusiveness; desire to be independent
Provider characteristics	Good reputation and consumer trust	Doubts about responsibilities and reliability
Perceived advantage	**Technical level of the product (i.e. better performance with service)** Ability to offer additional services or whole service ecosystem	Services are seen as more expensive

to the ease of the solution, a highly appreciated factor among consumers, and it would be stronger factor when the technical complexity of the product is higher. The technical level of the product itself also influenced its acceptability. As one consumer stated: '… [*when renting you will get*] *state-of-the-art technology, so your own device can become obsolete in 15 years, but rental companies hardly keep 15-year-old equipment.*' The respondents stated that they appreciated the possibility of getting better performance, e.g. laundering service rather than washing machine use by themselves.

Besides, only one previous study on car sharing services [24] mentioned the quality and reliability of the product and service (i.e. the offering) and the ability to offer additional services or a whole service ecosystem as important factors for acceptance of PSS. Our study confirms both factors in the context of CE-PSS. Additional circular services were appreciated by respondents in the context of home delivery services, such as those related to the recycling of bottles, clothes and other items. '*I would appreciate it if someone brought the TV, even if it didn't need any installation, to take the trash away…to recycling. Or if I happened to have other stuff, they* *would take it to recycling…*' Consumers, especially the elderly, were also interested in getting help from delivery staff in small maintenance tasks in the home, such as changing bulbs. Regarding furniture, respondents considered whether or not all furniture and fittings/accessories could be hired from the same place, and some of them would also be interested in including interior design services in the bundle. The ecological aspects in terms of readiness to use circular services varied. The conversation revealed that it is difficult for consumers to assess how environmentally friendly a product, service, or PSS is. They generally reflected on the ecological aspects of their consumption as a whole, and some mentioned a bad conscience: '*it's not ecological in any way…always with that moral pain I press the button* [to order something].'

Our analysis also revealed two factors hindering or preventing acceptance that had not been considered in previous PSS acceptance studies. We identified novel factors preventing acceptance that we refer to as: product characteristics leading to emotional investment by the consumer, and as consumer characteristics, i.e. personal identity, creating a strong relationship with the product itself.

Findings indicate that an intimate or emotional relationship with a product is a barrier to acceptance. An intimate form of attachment is present in a range of circumstances, e.g. when an object is deeply integral to private domestic life, such as a sofa. One respondent stated that she could not even consider renting a sofa because of the intimate domestic engagement she has with such items. As she stated, '*All layers of life relate to furniture. And I think that it would be terrible* [*to hire a couch*]; *I don't think that I would sit on a hired sofa. I would just keep it in a corner*.' On the other hand, for products with weak emotional links to the consumer, the barrier seems not to be present. For instant, as the same respondent amplified: '*I don't have any kind of need to own a washing machine. If I know that I can get a new one, let's say every second year, and it's brand new, and they will bring it and take care of it, and it's also cheaper compared to buying it myself, I would say yes to that model. It just sits in the corner; I do not have the same kind of relationship with it as I have with my couch.'*

Other respondents stated that they prefer to own as they do not want to commit to a service provider; they would rather put their efforts into repairing and maintaining products they own themselves, a preference that we labelled the desire to be independent. Also, when the ownership of a product is linked to personal identity, e.g. certain makes of vehicles or everyday clothing, products are used a lot and become extensions of the consumer or relate to meaningful life events, some respondents stated that it would be 'weird' or uncomfortable to hire these.

17.5 Concluding Remarks

Our findings suggest that the importance of emotional aspects of consumption and acceptance of circular solutions have yet to be properly considered in CE discussions. Emotional attachments to products and use of the product are deeply connected to the products' place and importance in everyday life habits, events, and memories. The aspect of fun and gaming in consumption is important part of consumer behaviour and increases the emotional attachment. Consumption theories in social sciences have stressed that products can be an extension of self and an important part of identity building. CE literature, on the other hand, has strong connections to engineering and technological changes in production systems. Also, the idea behind PSS is that consumers are looking for something other than the product itself, namely the end result or the function. The positivist-oriented CE discussion relies mainly on rational consumer behaviour theories stressing rational decisions based on price and functionality rather than emotional aspects of consumption from cultural and practice theories.

The emotional aspect explains the success of circular services and CE-PSS in the B2B sector where the decision making is more rational. The B2C sector, on the other hand, is still emerging, and there is a need to make circular offerings attractive to consumers. Hence, companies have to be able to offer the right price and quality but also understand consumers' emotional attachment to the products and services as well as their desire to be independent. Further research is needed to understand better consumers' emotional attachment to products and services and their concern about environmental impact of their lifestyle and consumption patterns.

Further research should focus on bringing multidisciplinary insights regarding emotional aspects to the design of circular offerings. Engagement with concepts and theories from cultural and practice theories will be necessary to advance knowledge and practice on CE-PSS and circular services. Moreover, new sustainability trends in product design could be helpful to enhance emotional engagement and attractiveness of products. Approaches such as Emotionally Durable Design, also named Design for Product Attachment, and Design for Sustainable Behaviour [43] could be considered to enhance probability of acceptance in circular offerings.

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Chapter 18
Microstructure and Mechanical Properties of IN738C Superalloy Fabricated by Laser Powder Bed Fusion

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Abstract IN738C is a widely utilized precipitation hardening nickel-based superalloy known for its excellent mechanical properties in various industries. Laser powder bed fusion (LPBF) has emerged as a highly advantageous additive manufacturing process for fabricating complex-shaped parts using metal powders. This study investigates the influence of process parameters, specifically the scanning speed and hatch spacing, on the defect formation in LPBF-manufactured IN738C alloy. Additionally, the microstructure of heat-treated IN738C samples is examined, and their mechanical properties are evaluated through ambient tensile testing. The results indicate that LPBF-produced IN738C alloy exhibits the highest density when using a hatch spacing of 90 μm and a scanning speed of 750 mm/s. Upon heat treatment, cracks within the material propagated. Microscopic analysis of the heat-treated specimens reveals the presence of precipitated carbides and the 03B3′ phase, with continuous carbides observed along the grain boundaries. The as-built (AB) specimens exhibit a medium result in ultimate tensile strength (UTS), yield strength (YS), and elongation. However, the heat-treated (HT) specimens fail prior to yielding, exhibiting a lower result in UTS and elongation than AB specimens.

18.1 Introduction

Nickel-based superalloys are extensively employed in applications that demand excellent mechanical properties at high temperatures, particularly within the aerospace industry. As operating temperatures continue to increase, the significance of precipitation hardening nickel-based superalloys becomes more pronounced across various sectors. IN738C, also known as Inconel 738C, represents a typical

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example of a precipitation hardening nickel-based superalloy. Due to its exceptional high-temperature performance and corrosion resistance, it has found widespread use in critical components such as the hot sections of gas turbine and jet engines, as well as nuclear reactor parts [1, 2].

The complexity of part geometries has grown, posing challenges for traditional machining methods in processing superalloys. Additive Manufacturing (AM), a novel fabrication technique, offers an alternative approach. Unlike conventional methods, AM constructs parts layer by layer, starting from scratch. By employing thinner layers and precise control of the scanning path, AM enables the production of parts with minimal dimensional errors. Theoretically, AM has the capability to manufacture parts with highly intricate geometries [3]. One specific AM technology is laser powder bed fusion (LPBF), which utilizes metal powder as the raw material. Through a cyclic process involving powder deposition and laser scanning, LPBF can fabricate parts which need little machining based on a computer-aided design (CAD) model. Compared with other manufacturing process, this feature allows LPBF to conserve energy and materials, making it a sustainable manufacturing process. At present, however, there are still some problems in LPBF-fabricated parts, which may lead to significant failures, causing a waste of materials. It has a great significance to sustainable manufacturing in research of the present problems.

In recent years, significant research efforts have been devoted to exploring the fabrication of nickel-based superalloys using LPBF. Ma et al. [4] reported that liquation cracks were the primary defect observed in LPBF-fabricated IN738 alloy [4]. The influence of scanning strategies [5, 6] and heat treatment methods [7] on the crack density of IN738 alloy has been investigated. It has been established that selecting appropriate process parameters can reduce crack density; however, completely eliminating cracks remains a challenge [5–7]. The present study aims to investigate the impact of hatch spacing and scanning speed on the occurrence of defects in LPBF-fabricated IN738C. Additionally, the cracking mode of IN738 alloy is examined. Subsequently, the microstructure of IN738 is studied following heat treatment, and a tensile test is conducted to assess the effect of heat treatment on the mechanical properties of the specimens.

18.2 Experimental Procedure

18.2.1 Material and Manufacturing Processes

The feedstock of IN738C (Avimetal AM) used in this study was produced through vacuum atomization. The composition of the IN738C powder is provided in Table 18.1. The particle size distribution of the powder, characterized by the D10, D50, and D90 values, is detected to 19.1 μm, 33.3 μm, and 55.1 μm, respectively.

All specimens in this study were manufactured on 45-steel substrates, using a Concept Laser Mlab cusing 200R laser powder bed fusion (LPBF) machine under an

Table 18.1 Actual chemical composition of the IN738 powder

Element	Cr	Co	W	Mo	Al	Ti	Nb	Ta	C	Ni
wt.%	15.92	8.12	2.61	1.8	3.6	3.49	0.94	1.78	0.17	Bal

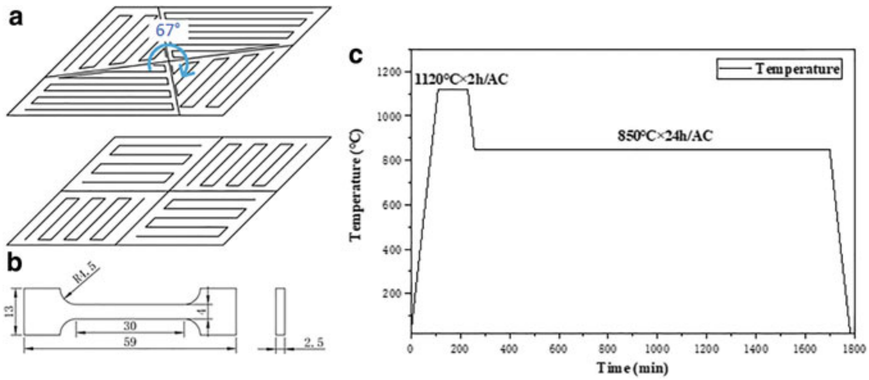

Fig. 18.1 Specimen **a** scanning strategy, **b** heat treatment strategy, and **c** tensile bar

argon atmosphere. The LPBF machine was equipped with a 200W ytterbium fiber laser operating at a wavelength of 1070 nm. The laser had a Gaussian spot size of approximately 70 μm.

To optimize the scanning speed and hatch spacing, two groups of cubic specimens measuring 7 × 7 × 8 mm were initially fabricated. These groups were divided based on different hatch spacings, namely 90 and 110 μm. The main process parameters were kept constant during this optimization process. The laser power used was set at 190 W, and the layer thickness was maintained at 40 μm. The scanning strategy employed was a chessboard pattern, with each island having a side length of 5 mm. In each layer, the scanning direction was rotated by 90°, while the chessboard pattern was rotated by 67°, as depicted in Fig. 18.1a.

Tensile test specimens, in the form of panels measuring 2.5 × 65 × 14 mm, were subsequently manufactured using the optimized parameters obtained from the cubic specimens. The optimal parameters consisted of a hatch spacing of 90 μm and a scanning speed of 750 mm/s. Alongside the tensile specimens, cubic specimens were also fabricated to facilitate microstructure observations.

Heat treatment was conducted using a tubular furnace under an argon atmosphere. The heat treatment strategy employed in this study is illustrated in Fig. 18.1b. It consisted of a solution treatment carried out at 1120 °C for 2 h, followed by an aging treatment at 850 °C for 24 h. To ensure the desired treatment conditions, the specimens were placed into the furnace once the temperature reached the prescribed treatment temperature. After each heat treatment stage, the specimens were air-cooled (AC) to ambient temperature.

18.2.2 Microstructure Observation

The cubic specimens were cut using wire cutting parallel to the build direction. The cut sections were then ground sequentially using SiC sandpaper with grit sizes of 320, 600, 1500, and 2500 mesh. Following the grinding process, the samples were polished using polishing suspensions of 3, 1, and 0.04 μm.

The polished specimens were initially examined using an optical metallographic microscope to evaluate the presence of defects such as lack of fusion, microcracks, and keyholes. The optimization of LPBF parameters was performed under the optical observation with a magnification of 50 times. The parameters of cubic specimen with less lack of fusion and keyhole defects were selected to be optimal. Also, 5 areas were observed and averaged for each specimen in the optimization. For microstructure observation, scanning electron microscopy (SEM) was utilized, specifically the JEOL JSM-7800F model. To further analyze the microstructures, the specimens were etched in a 15% oxalic acid solution using a 5 V direct current. Energy-dispersive X-ray spectroscopy (EDS) equipped on the Zeiss Gemini500 SEM was employed to analyze the micro-segregation of elements within specific regions of interest.

To determine the average diameters of carbides and γ' phase, the 'Analyze particles' function in the ImageJ software was utilized. The measurements were subsequently calculated using Excel. In order to ensure data reliability, any unreasonable data points, such as particles with only a few pixels, were manually excluded from the analysis.

A single path LPBF simulation was carried out by the Flow3D software to understand the mechanism of the cracks observed in LPBF-fabricated IN738C. The parameters used in the simulation were set according to the optimized LPBF process parameters and physical properties of IN738 superalloy.

The JMatPro software was utilized in the equilibrium thermodynamic simulation of IN738 used in the experiment. The simulation was carried out over a temperature range from 1400 to 600 °C, with a step of 1 °C. The simulation output includes the weight fractions of the various phases at each temperature steps.

18.2.3 Tensile Test

The tensile specimens were fabricated as panels, using the optimized parameters obtained from the previous fabrication process. Subsequently, half of the panels underwent a standard heat treatment same as mentioned in Sect. 2.1, which consisted of a solution treatment at 1120 °C for 2 h, followed by an aging treatment at 850 °C for 24 h, with air cooling (AC) after each stage.

Plate tensile bars, both as-built (AB) and heat-treated (HT), were obtained by wire cutting from the panels, ensuring that the load direction was perpendicular to the build direction. The dimensions of the tensile specimens, designed according to the GB/T 228.1-2021 standard, are illustrated in Fig. 18.1c.

The tensile tests were performed using a universal testing machine, applying a constant strain rate of 0.067 min^{-1} at ambient temperature. To minimize errors, two specimens from both the AB and HT groups were tested.

18.3 Results and Discussion

18.3.1 Characterization of Defects in LPBF-Fabricated IN738C

The polished specimens were examined using an optical metallographic microscope. Keyholes were only observed in specimens fabricated at low scanning speeds, whereas lack of fusion was observed in specimens fabricated at high scanning speeds. Microcracks were observed in all specimens, regardless of scanning speed.

Notably, specimens fabricated at medium scanning speeds exhibited a lower cracking density compared to those at other scanning speeds, regardless of the hatch spacing (90 and 110 μm). Among the specimens in the 90 μm group, a lower cracking tendency was observed compared to the 110 μm group across all scanning speeds. Specifically, the specimen fabricated at a scanning speed of 750 mm/s in the 90 μm group exhibited the lowest cracking tendency among all specimens, characterized by a lower cracking density and smaller microcracks.

In contrast to previous research [4], the present study identified two primary types of microcracks in LPBF-fabricated IN738C: solidification cracks and solid-state cracks, as depicted in Fig. 18.2a. Solidification cracks are characterized by their width and winding patterns, which are often aligned horizontally to the build direction. Figure 18.2b illustrates a typical example of a solidification crack, with the winding portion situated in the middle. Upon closer examination, dendrite arms were observable within the crack structure. On the other hand, solid-state cracks tend to be thinner, straighter, and exhibit a small winding tail at the end. Moreover, solid-state cracks display symmetrical edges, which is not the case for solidification cracks. Within LPBF-fabricated IN738C specimens, approximately half of the observed cracks are solidification cracks, while the remaining half are solid-state cracks. Notably, the length and density of the cracks exhibit significant variation, both within specimens fabricated using the same parameters and among those fabricated using different parameters. The minimum crack length and density were achieved when employing a hatch spacing of 90 μm and a scanning speed of 750 mm/s.

The cracking density in LPBF-fabricated specimens exhibited significant variation depending on the selected process parameters. Specifically, the cracking density demonstrated an initial decrease followed by an increase with increasing scanning speed, while the hatch spacing remained constant. Moreover, the type of defects observed varied with changes in scanning speed, transitioning from a combination of keyhole defects and cracking, to solely cracking, and eventually to lack of fusion

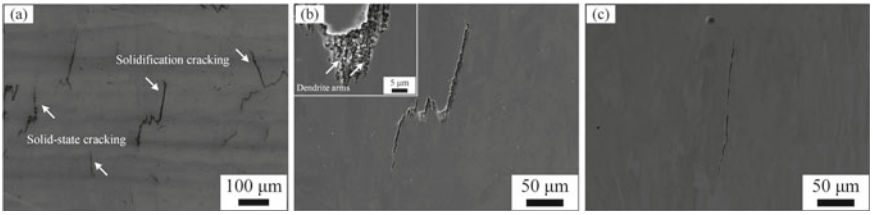

Fig. 18.2 Backscattered electron imaging SEM micrographs of microcracks in as-built LPBF-fabricated IN738 specimen **a** overview, **b** solidification cracking, and **c** solid-state cracking

and cracking as the speed rises. These changes in defect type can be attributed to alterations in energy density among the specimens.

At lower energy densities, the metal powders may not fully melt, resulting in the occurrence of lack of fusion defects. Conversely, higher energy densities can lead to excessive heating, resulting in the formation of keyhole defects where the fused metal boils and creates voids. Cracking defects can arise due to inadequate bonding strength resulting from lower energy densities, while higher energy densities can contribute to greater residual stress, increasing the likelihood of cracking. The lowest cracking density appeared at a 70.37 J/mm^3 volume energy density, which is included in 64.9–118.6 J/mm^3 in the previous research [5]. These factors related to energy density are considered to be the main driving force behind the observed variations in cracking density.

In LPBF-fabricated specimens, two distinct types of cracks were observed: solidification cracks and solid-state cracks. Figure 18.3 provides an illustration of the three main zones present during the scanning process: the melt pool, the transition zone, and the heat-affected zone. Solidification cracks predominantly manifested at the boundary between the melt pool and the transition zone. During the solidification process, the unsolidified liquid film situated between the dendrites became unable to withstand the tensile stress, resulting in the formation of solidification cracks. These cracks were characterized by the presence of dendrite arms, indicative of their occurrence during the solidification phase.

On the other hand, solid-state cracks primarily appeared in the heat-affected zone. The LPBF process subjected the specimens to a thermal cycle, inducing thermal stress within the heat-affected zone. Solid-state cracks formed when the thermal stress exceeded the material's limit of resistance. These cracks exhibited symmetrical edges and typically had a sharp, winding termination, suggesting they were formed through tearing after the solidification stage.

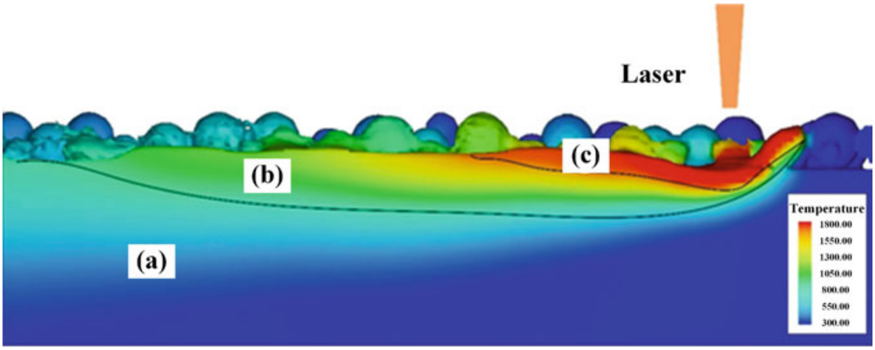

Fig. 18.3 Three zones existed in LPBF process **a** heat-affected zone, **b** transition zone, and **c** the melt pool

18.3.2 *Characterization of Heat-Treated IN738C*

In comparison to the as-built specimens, the heat-treated specimens exhibited longer and wider solid-state cracks. Figure 18.4 illustrates the morphology of the solid-state cracks, which appeared elongated and wider, while the solidification cracks seemed to be stretched, displaying a longer edge compared to the cracks observed in the as-built specimens. During the LPBF process, significant thermal stress is generated, some of which is relieved through cracking, while the remaining stress is retained within the fabricated specimens. This retained stress can be released through recrystallization or by cracking during the heat treatment process, thereby elongating the existing cracks present in the specimens. According to a previous study carried out by Zhang et al [8], the microcracks generally occurred on the grain boundaries.

The etched specimens were examined using SEM, and the results are presented in Fig. 18.5a. The grains exhibited a columnar morphology, with dark lines observed at the grain boundaries. Figure 18.5b provides a micrograph of the grain boundaries,

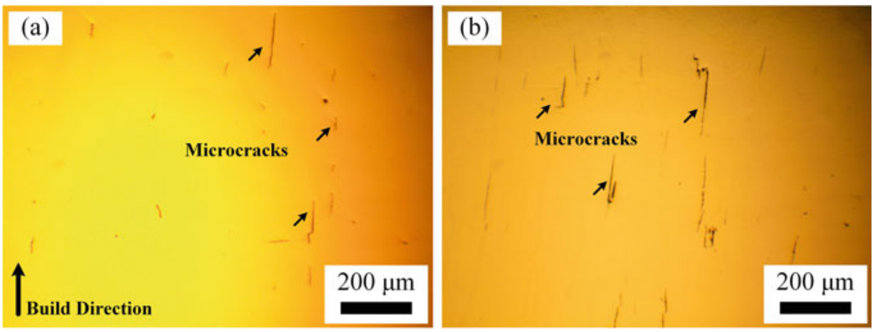

Fig. 18.4 Optical micrographs of **a** as-built specimen, and **b** heat-treated specimen under same LPBF process parameters

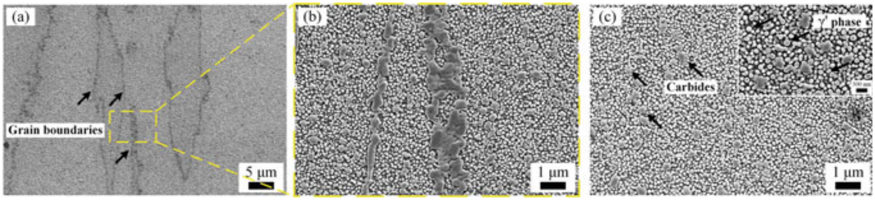

Fig. 18.5 Secondary electron (SE) imaging SEM micrographs of heat-treated specimens **a** overview, **b** micrograph near grain boundaries, and **c** micrograph in a grain

where irregularly shaped dark precipitates were found continuously aligned along the grain boundaries. EDS mapping analysis revealed a deficiency of Ni, Co, and Al at the location of the precipitates, while an accumulation of Ta, W, Cr, Nb, and C was observed at the same position, as shown in Fig. 18.6. This observation suggests the precipitation of carbides at the grain boundaries following the heat treatment. Based on the concentrated elements detected in the precipitates, it can be inferred that the carbides consist of MC and M23C6 phases. Equilibrium thermodynamic simulations of IN738C indicate that at high temperatures, the carbides primarily exist as MC. However, at approximately 1093 °C, the MC carbides begin to transform into M23C6 carbides. At around 981 °C, the M23C6 carbides become the sole type of carbide present in the IN738C superalloy. The observed mixture of MC and M23C6 carbides suggests that the carbide transformation in the LPBF-fabricated specimens was not fully completed under typical heat treatment conditions.

In Fig. 18.5c, a micrograph inside a grain is shown. Irregularly shaped carbides were observed to be dispersed evenly throughout the matrix, with an average diameter of 309.5 nm. Additionally, small spherical precipitates with an average diameter of 159.2 nm were uniformly distributed within the matrix. These observations indicate the precipitation of the γ' phase ([Ni_3(Al, Ti)]). The γ' phase is a crucial strengthening phase in precipitation hardening nickel-based superalloys, particularly at high temperatures. The morphology of the γ' phase can vary and may appear as spherical, irregular, or cubic shapes depending on the diameter of the precipitates. Generally, the presence of spherical γ' phase morphology corresponds to excellent mechanical properties. The observation of spherical γ' phase indicates that the heat treatment regimen employed in this study was appropriate. Together with the precipitation of carbides, the uniform precipitation of the γ' phase contributes to the strengthening of the IN738C alloy [9].

18.3.3 Ambient Temperature Tensile Test

The results of the ambient temperature tensile tests for both as-built (AB) and heat-treated (HT) IN738C specimens are presented in Fig. 18.7. The AB specimens exhibited an ultimate tensile strength (UTS) of 811.6 ± 4.7 MPa, a yield strength (YS) of

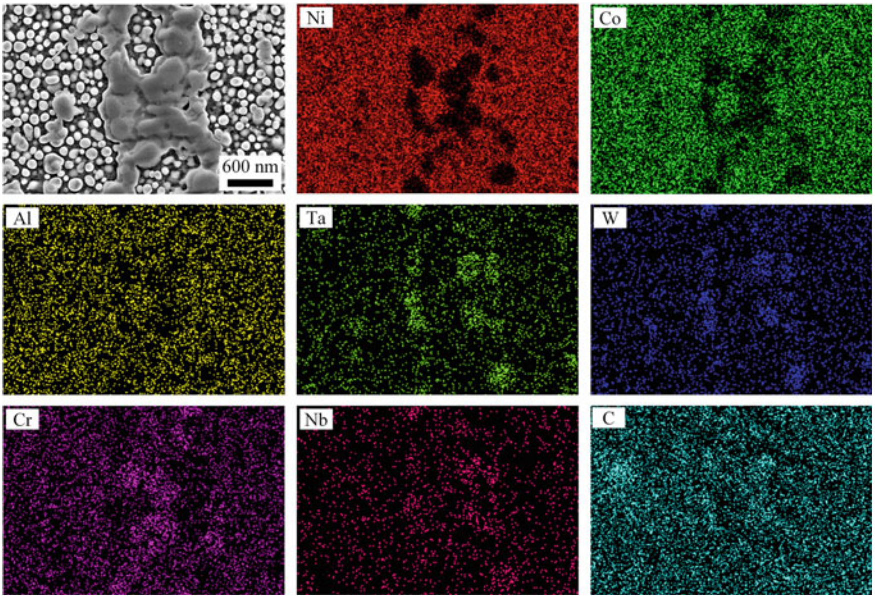

Fig. 18.6 Energy-dispersive X-ray spectroscopy (EDS) mapping of the precipitates on the grain boundaries in heat-treated specimens

600.8 ± 6.1 MPa, and an elongation of 10.35 ± 0.17%. In contrast, the HT specimens experienced failure before yielding, with a UTS of 673.4 ± 18.45 MPa and an elongation of 4.21 ± 0.06%. The UTS of AB specimens was lower than the value reported in previous study, while elongation was much higher. The HT specimens got both a lower UTS and elongation [5].

The low tensile properties of the AB IN738C specimens can be attributed to the presence of microcracks within the specimens. These microcracks can serve as stress concentrators and become the initiation points for failure during the tensile testing. Additionally, the presence of microcracks reduces the effective area available to withstand tensile stress, further contributing to the poor performance of the AB specimens.

Although the heat treatment resulted in the precipitation of strengthening phases, the HT specimens exhibited worse tensile properties compared to the AB specimens. This can be attributed to the more severe cracking observed in the HT specimens, which led to failure occurring earlier before the specimens could yield.

Overall, the presence of microcracks in the AB specimens and the increased cracking in the HT specimens negatively impacted their tensile properties, resulting in reduced strength and elongation compared to the desired performance.

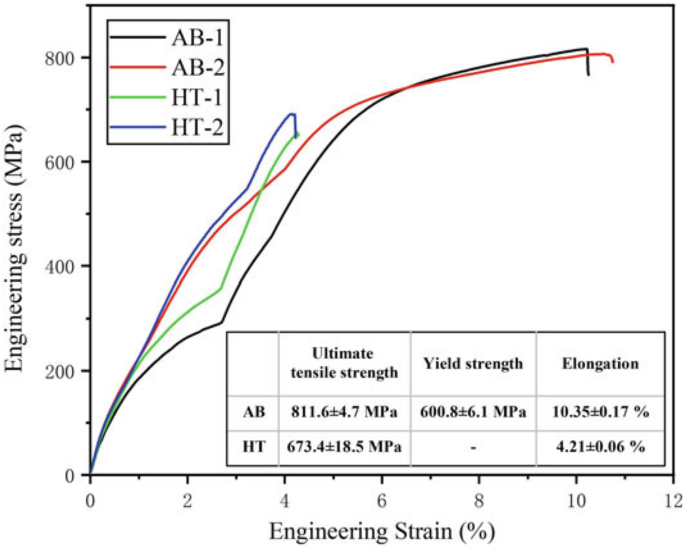

Fig. 18.7 Ambient temperature tensile test

18.4 Conclusion

This study optimized the hatch spacing and scanning speed of IN738C in LPBF processing. The main findings of the study can be summarized as follows:

(1) Different types of defects were observed in LPBF-fabricated IN738C, including lack of fusion, cracking, and keyhole. It was found that a parameter combination with relatively lower cracking density could be achieved. Lack of fusion and keyhole defects could be eliminated with appropriate process parameters, but cracking could not be completely eliminated even with parameter optimization. The lowest cracking density was observed when the hatch spacing was 90 μm and the scanning speed was 750 mm/s. After heat treatment, cracks in the specimens elongated.

(2) SEM observations of the heat-treated specimens revealed the presence of continuous carbides at the grain boundaries. EDS mapping indicated the concentration of Ta, W, Cr, Nb, and C, suggesting the presence of MC carbides and M23C6 carbides. Smaller carbides were also observed inside the grains, with an average diameter of 309.5 nm. Additionally, spherical γ' phase with an average diameter of 159.2 nm uniformly precipitated in the matrix after heat treatment.

(3) The tensile test of the as-built specimens at ambient temperature showed an ultimate tensile strength (UTS) of 811.6 $\pm$ 4.7 MPa, a yield strength (YS) of 600.8 $\pm$ 6.1 MPa, and an elongation of 10.35 $\pm$ 0.17%. However, the heat-treated specimens failed before yielding, with a lower UTS of 673.4 $\pm$ 18.45 MPa and

a reduced elongation of $4.21 \pm 0.06\%$. The decrease in mechanical properties was mainly attributed to the increase of the microcracks.

Overall, the study highlighted the challenges of eliminating cracking in LPBF-fabricated IN738C, the presence of carbides and γ' phase after heat treatment, and the impact of heat treatment on the mechanical properties of the alloy.

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Chapter 19
A Heuristic Approach to Design a Crowd-Based Last-Mile Delivery Network

Marco Bortolini, Francesca Calabrese, Emilio Ferrari, Francesco Gabriele Galizia, and Ludovica Diletta Naldi

Abstract Crowd logistics (CL) rose in the last years as an effective strategy to manage last-mile deliveries, especially in urban areas, which are often one of the main causes of the increased road traffic and, at the same time, negatively impacting on the environment. Within CL, the last-mile delivery is entrusted to the crowd, i.e. normal people willing to finalize the delivery, deviating as little as possible from their standard route, in exchange for an economic remuneration. In this context, this paper proposes a three-step heuristic approach to design a crowd-based last-mile delivery network, managing the whole process from the delivery of the goods in intermediate lockers by traditional shippers, up to the delivery to the final customers by occasional drivers (ODs). The proposed integrated approach is applied to the case study of the city of Bologna (Italy) to showcase its effectiveness. In fact, the city of Bologna is fully suitable for the implementation of CL due to the presence of traffic regulations in the city centre and for the high presence of university students which can potentially serve as OD.

19.1 Introduction and Literature Review

Last-mile logistics currently represents the least efficient stage within supply chain management (SCM), responsible for about 30% of the total delivery cost and of significant environmental emissions. However, the increasing use of e-commerce and the customer need to get the goods in short time ask for a complete redesign of the parcel delivery system strategies, especially in urban areas, which are often the most congested areas in terms of traffic jam, and often subject to traffic restrictions [1–5]. Sustainable mobility is one of the main areas of investigation by the European Commission to implement, among the others, smart traffic management systems and

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to improve traditional freight delivery methods. Sustainable and efficient solutions have to be implemented in the mid-term to optimize urban parcel delivery. In the recent years, crowd logistics (CL) rose as one of the most promising strategies. In this logic, traditional couriers deliver the products to intermediate transfer points, i.e. lockers [6–10]. Then, normal people, available to perform the last-mile delivery, pick the product and deliver it to the final customer [11]. In this context, the term "crowd" refers to normal people, i.e. non-professional drivers, available to perform a deviation from their standard route to finalize the delivery for a small fee, using their own means of transport, or simply walking or cycling, avoiding traffic congestions [12]. Among the main benefits from adopting this strategy, we can mention the ease of recruiting CL partners and that the required resources to finalize the deliveries are traditionally owned by ordinary people [13].

Current literature proposes a wide set of models and quantitative methods to designing CL-based last-mile delivery networks. Kafle et al. [2] proposed a CL system for urban parcel relay and delivery, considering cyclists and pedestrians as OD. The problem is formulated as a mixed integer nonlinear program to simultaneously select the ODs and to determine the relay points and truck routes and schedule, solved through a Tabu search algorithm (TSA). Huang and Ardiansyah [11] defined a mixed integer programming model supporting the planning of last-mile deliver networks to determine customers to be outsourced, by which partners and at which transfer point, highlighting that well-planned crowdsourcing integration can take benefit of the flexibility and cost saving of crowdsourcing for last-mile delivery. Wang et al. [6] proposed a large-scale mobile CL tasking model involving a large pool of ODs to perform the last-mile delivery. The model is defined as a min-cost flow problem solved through pruning techniques to reduce the network size and applied to the contexts of Singapore and Beijing. Other studies quantitatively modelled the concept of CL as a vehicle routing problem with occasional drivers (VRPOD) [14–18]. Following this stream, Akeb et al. [17] faced the problem of parcel return, if the customer is away from home at the delivery moment, generating additional reverse logistics costs. The authors proposed a CL-based solution aiming at using neighbours to collect and deliver the parcels. The proposed method was tested on a district of Paris, getting encouraging results. Archetti et al. [18] proposed a model for the design of a crowd-based network model with the main objective to minimize the total cost in the form of a capacitated vehicle routing problem. The authors designed a heuristic procedure to solve the model, providing valuable insights about the potential of using ODs to reduce the total delivery costs.

In this scenario, this paper proposes a three-step heuristic approach to support in the design and implementation of a crowd-based last-mile delivery network, providing the assignment of products to lockers and of the most suitable ODs for product picking and final delivery to customers. The algorithm is implemented in Microsoft Excel, providing a ready- and easy-to use tool for CL practitioners.

According to this background, the remainder of this paper is organized as follows. Section 19.2 introduces and defines the three-step heuristic approach for crowd-based last-mile delivery network design. Section 19.3 applies the model to the reference case of the city of Bologna (Italy) and discusses the main results. Finally, Sect. 19.4 concludes the paper with final remarks and future opportunities for research.

19.2 A Heuristic Approach to Design a Crowd-Based Last-Mile Delivery Network

The considered crowd-based last-mile delivery network rises as a two-level distribution chain. In the first stage, traditional couriers depart from the central warehouse to ship the goods to intermediate lockers. In a second stage, ODs visit the lockers to pick the goods and finalize the final deliveries to customers. The model considers the presence of time windows to ensure the system dynamics, and in each time window, the delivery of a parcel to a single final customer is guaranteed. Since ODs need to deviate from their original route to perform the delivery, the model attempts to perform an intelligent assignment of the goods to the available ODs, considering a maximum acceptable deviation of the ODs to minimize the distances they need to cover.

In the procedure development, the following assumptions are adopted:

- goods for a single customer cannot be splitted in more deliveries;
- customers are served by ODs, only;
- possible missed deliveries caused by absence of customers are not considered;
- small parcels suitable for the transport by ODs are allowed.

Next Fig. 19.1 shows a schematic representation of the network.

The presence of time windows to give dynamics to the system behaviour adds complexity towards an efficient model solving. Hence, following trends from the

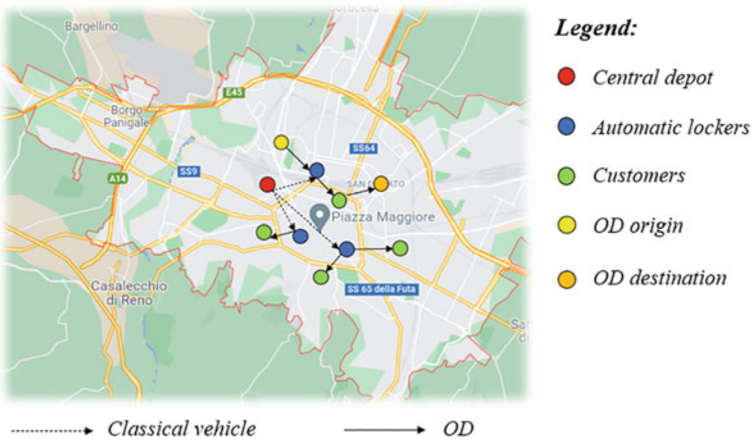

Fig. 19.1 Network schematic representation

recent literature on the topic [17, 18], a heuristic-based approach is developed. The detailed mathematical formulation of the model behind the heuristic formulation is omitted for the sake of brevity. However, the cost-based objective function characterizing the original model attempts to minimize the cost of the fleet of classic vehicles, e.g. trucks, owned by traditional couriers that have to replenish the intermediate lockers, the costs associated to the fuel consumption necessary to replenish the lockers, the cost of activating and using lockers for parcel deposit/withdrawal, and lastly, the cost for ODs service and remuneration. The heuristic approach proposed in this study is designed into three main blocks, i.e. (1) preliminary assignment of the goods to the intermediate lockers, (2) replenishment of the lockers by professional shippers, and (3) picking of the parcel by ODs and final delivery to customers. Three algorithms are designed to manage each of the above-described steps, and they are each other linked since the output of the first algorithm is the input of the other two. In detail, a greedy algorithm is designed to manage step 1 and 3, while a shortest path algorithm is defined for step 2. Step 3 rises as the most innovative one, and it is the key point of the whole procedure. The whole algorithm is designed to minimize the distances travelled by all the actors involved in the network, leading to the minimization of the transport costs, following the logic of the optimization problem behind the algorithm. Figure 19.2 shows a block diagram highlighting the logical working of the procedure.

About the step 1 of the algorithm, devoted to the assignment of customer parcels to specific intermediate lockers, a greedy algorithm has been defined. The procedure requires as input, as Microsoft Excel dataset, details about customer orders, i.e. customer destination with latitude and longitude data, and customer time windows in which it is required to finalize the delivery. As preliminary operation, the customer orders are sorted according to the urgency with which they need to receive the parcel. In another sheet, data about locations of the available intermediate lockers for the temporary storage of parcels are detailed, with relative latitude and longitude data. The results of the step 1 simulation are collected in a last sheet, containing the final assignments of the parcels to the optimal lockers, computed by minimizing the distance among intermediate lockers and final customers, which will then be entered as input to the next steps of the procedure.

The step 2 of the algorithm is devoted to determining the best sequence of visits to lockers by traditional couriers, with the aim of minimizing the travelled distances. The problem rises as a vehicle routing problem (VRP), and the designed algorithm is a shortest path type. Hence, traditional couriers leave from a central depot, deliver the parcels to specific lockers, because of step 1, and going through a specific visit sequence, because of step 2. After finalizing the deliveries, traditional couriers come back to the central depot. The designed shortest path algorithm allows, excepts for the central depot, a node, i.e. a locker, to be visited only once. Moreover, since the number of customers present in the system is quite acceptable, the parcels transported are usually small, and the presence of only one vehicle driven by a traditional courier is considered, which supplies all the lockers.

Step 3 is the core of the CL logic, since in this phase the ODs pick the parcels from the intermediate lockers and finalize the delivery to the final customers. In detail, the

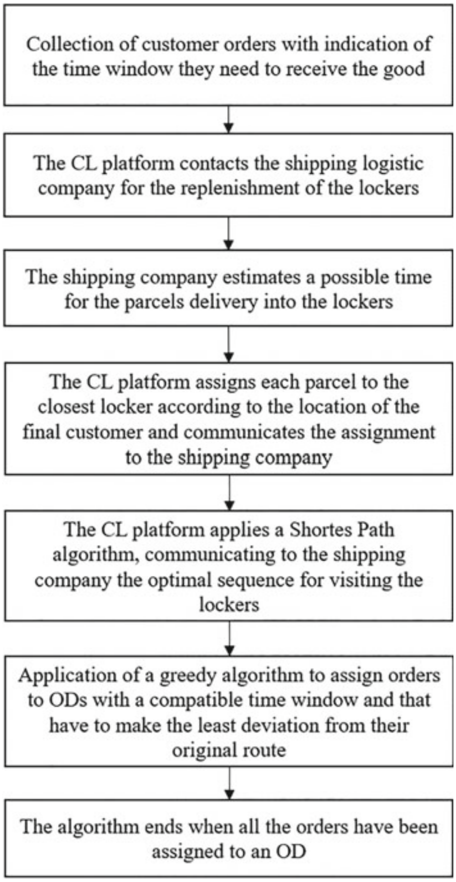

Fig. 19.2 Block diagram of the designed algorithm

OD deviates from its original route to pick the parcel from the locker, to finalize the delivery to the customer destination and, finally, to go to his/her destination. A time window is associated to each OD, indicating his/her availability. This time window needs to match with the availability time window indicated by the customers. In presence of a match and assignment of an OD to a customer, the two actors agree on a specific time for delivery. Each OD performs a single delivery to a single customer within a time window, then he/she can remain into the system and, eventually, give his/her available to perform other deliveries in additional time windows. The algorithm designed for step 3 is greedy, acting as follows: The collected orders are sorted according to the urgency of the respective customers' time window, and, following the priorities, each delivery request must be associated to the best available OD, i.e. the one which, among the ODs with a time window compatible with that of the customer, guarantees the least deviation from its original route, to minimizing the global distances travelled by the ODs. One customer at a time is considered, whose order is assigned to the optimal OD, then proceeding with subsequent customers, until all order-OD assignments have been completed.

The algorithms are developed through the Visual Basic for Applications (VBA) tool of Microsoft Excel on a personal computer equipped with an Intel Core i7-7500U CPU @ 2.70–2.90 GHz, 64-bit OS and 8 GB RAM installed. The aim was to design a fully flexible algorithm, giving the possibility to the final users to set the number of intermediate lockers, ODs and final customers present into the system.

Next Sect. 19.3 applies the proposed methodology to the case study of the city of Bologna (Italy).

19.3 Case Study and Results

The proposed algorithm is applied to the real case of the urban area of the city of Bologna (Italy), which counts 392′472 inhabitants and home of the ancient University in the western world. The high number of students, always looking for occasional jobs, makes Bologna suitable for the implementation of a CL-based system. A relevant aspect characterizing the urban area of the metropolitan city of Bologna is the huge presence of limited traffic zones (ZTL), covering a relevant area of the city, as in Fig. 19.3.

In fact, more than 50% of the area of Bologna falls within one of the ZTL. The proposed case study considers the presence of three intermediate lockers, 12 ODs and 8 final customers. The Amazon DER5 warehouse, located in Calderara di Reno, i.e. a small town few kilometres away from Bologna, is selected as central depot, while the remaining actors, i.e. lockers, and location of ODs and customers, are in the city centre of Bologna, in the green area highlighted in Fig. 19.3. The selected

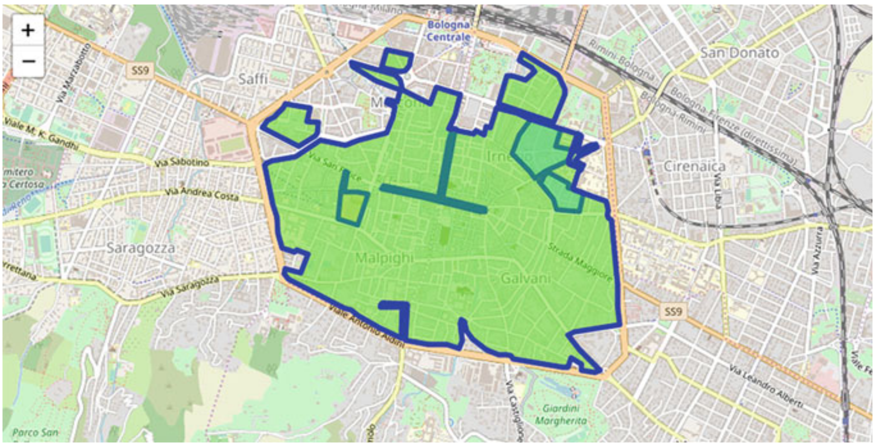

Fig. 19.3 LTZ of the city of Bologna (Italy)

Fig. 19.4 Case study, Amazon lockers (in green circles)

automatic lockers are the real Amazon Hub lockers named “Giove”, “Evasio” and “Creso”, located in Marconi Street, Oberdan Street, and Verdi Square, respectively, as in Fig. 19.4.

The time windows indicating the availability slots of the ODs and final customer destinations are other relevant input data. In particular, the ODs time windows are set mainly in the afternoon or evening time, in which, according to recent literature [12], they are more available. While all the considered addresses are identified on Google Maps (www.google.it/maps) in a way to cover approximately the entire area of the city centre of Bologna.

For the considered case study, next Tables 19.1, 19.2, and 19.3 show the output of each step of the algorithm, respectively. Table 19.1 shows the customer-locker assignment performed minimizing their distances.

Table 19.2 summarizes the results coming from the application of the shortest path algorithm to determining the best sequence of visits to lockers by traditional couriers, with the aim of minimizing the travelled distances. Results show that the optimal visit is Depot-L1-L3-L2. Finally, Table 19.3 allows to compute and visualize all the key information relating to all the completed customer-OD assignments.

Table 19.3 shows the customer orders and the time windows in which they have to be fulfilled, together with the proper assignment to the available and most suitable OD, with the global aim to minimize their overall travelled distances.

Overall, so far CL has been mostly implemented in the food sector by European and American companies. Relevant reference examples come from Foodora GmbH, UberEats and GrubHub Inc. Among the mail limitations of the approach,

Table 19.1 Output of algorithm step 1, customer-locker order assignment

	Customer ID	Locker location	Distance locker—customer (km)
Assignment 1	UYN	Marconi street 29, L1	0.84
Assignment 2	GKL	Oberdan street 37, L3	0.22
Assignment 3	PLM	Marconi street 29, L1	1.11
Assignment 4	AVP	Verdi square 2, L2	0.34
Assignment 5	LCS	Oberdan street 37, L3	0.59
Assignment 6	SQY	Marconi street 29, L1	0.61
Assignment 7	RWV	Verdi square 2, L2	0.92
Assignment 8	XDB	Verdi square 2, L2	0.53

Table 19.2 Output of algorithm step 2, distance matrix (km)

Location depot/ lockers (L)	Calderara di Reno, depot	Marconi street 29, L1	Verdi square 2, L2	Oberdan street 37, L3
Calderara di Reno, depot	–	*6.10*	7.05	6.56
Marconi street 29, L1	6.10	–	1.26	*0.76*
Verdi square 2, L2	7.05	1.26	–	0.54
Oberdan street 37, L3	6.56	0.76	*0.54*	–

security concerns can arise by customers due to a lack of trust towards the ODs. It would be useful to pursue partnerships with logistics and delivery companies that are experienced CL systems, e.g. DHL, for the implementation of such a platform to encourage user participation and mitigate such concerns. These companies, thanks to their know-how in the field and their solid reputation, could guarantee high-quality standards [12].

19.4 Conclusions and Future Research

In these recent years, pushed by the boom of the e-commerce, crowd logistics (CL) rose as an efficient last-mile delivery system, particularly in urban areas, to reduce the global transport and delivery costs and the related environmental emissions, positively affecting pollution and urban traffic. CL entrusts the management of the last-mile delivery to the crowd, i.e. normal people, willing to give their availability to perform some last-mile delivery deviating from their original route, in exchange for a small reward. Such people are called occasional drivers (ODs) and typically are workers or students, using their own or public means of transport to finalize their delivery tasks, picking up the parcels from intermediate storage points, i.e. lockers.

Table 19.3 Output of algorithm step 3, customer-OD order assignment

	Customer ID	Customer time window start	Customer time window end	OD ID	OD time window start	OD time window end
Assignment 1	UYN	March 24, 2023—3 pm	March 26, 2023—3 pm	ZSG-3	March 25, 2023—1 pm	March 27, 2023—7 pm
Assignment 2	GKL	March 24, 2023—7 pm	March 26, 2023—7 pm	ASX-1	March 23, 2023—5 pm	March 26, 2023—8 pm
Assignment 3	PLM	March 25, 2023—4.30 pm	March 27, 2023—12 pm	TYQ-4	March 26, 2023—12 pm	March 28, 2023—8 pm
Assignment 4	AVP	March 25, 2023—12 pm	March 27, 2023—4.30 pm	YHN-7	March 26, 2023—5.30 pm	March 28, 2023—1.30 pm
Assignment 5	LCS	March 25, 2023—14 pm	March 27, 2023—6 pm	ASX-1	March 26, 2023—8 pm	March 27, 2023—8 pm
Assignment 6	SQY	March 26, 2023—9 am	March 28, 2023—9 am	HKF-12	March 27, 2023—4 pm	March 29, 2023—6 pm
Assignment 7	RWV	March 27, 2023—5.30 pm	March 29, 2023—10 am	SJP-8	March 27, 2023—7 pm	March 29, 2023—12.30 pm
Assignment 8	XDB	March 28, 2023—6.30 pm	March 29, 2023—5 pm	SJP-8	March 29, 2023—12.30 pm	March 30, 2023—12.30 pm

Current literature proposes a wide set of optimization models to design crowd-based delivery networks. However, these models are usually NP-hard, and heuristic and easy-to-use approaches for logistics partners or companies interested in applying CL are missing but highly expected.

In this scenario, this paper proposes a preliminary three-step heuristic approach to support in the design and implementation of a crowd-based last-mile delivery network, providing the assignment of products to lockers and of the most suitable ODs for product picking and final delivery to customers. The algorithm is implemented in Microsoft Excel and applied to the reference case study of the city of Bologna (Italy), providing a ready- and easy-to use tool for CL practitioners.

Future research deals with the testing and validation of the approach to larger instances, including a higher number of actors among customers, ODs and intermediate lockers.

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Chapter 20
A Data-Driven Approach to Predict Supply Chain Risk Due to Suppliers' Partial Shipments

Matteo Gabellini, Francesca Calabrese, Lorenzo Civolani, Alberto Regattieri, and Cristina Mora

Abstract Supply chain resilience has been identified as a pillar of the new Industry 5.0 paradigm, and artificial intelligence and, in particular, machine learning have been indicated as effective tools to obtain it. However, although a vast amount of qualitative literature highlighted the capability of these technologies, further knowledge about how to properly design and use these tools to manage supply chain risk proactively and thus gain resilience needs to be produced. Indeed, some gaps have been noticed by analyzing the literature proposing approaches for proactively dealing with supply risks. In particular, no predictive approaches have been designed to deal with the operational risk related to the increased workload produced in the material acceptance department generated by suppliers' partial shipment practices. This paper thus proposes a predictive approach based on ARIMAX model to cover this gap. The proposed approach has been tested in an Italian automotive company, and its performance has been compared with other widely adopted forecasting approaches based on both traditional and deep learning models. Results have highlighted the advantages of the proposed approach in terms of accuracy and time required to build the predictive model. Furthermore, the proposed approach has revealed stable accuracy performance in both short-term and long-term forecasts, resulting in proper support for both short- and long-term planning activities.

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20.1 Introduction

Sustainability, human centricity, and resilience have been identified as the new goals of the Industry 5.0 paradigm [1, 2]. Since the introduction of the Industry 4.0 paradigm at the Hannover Fair in 2011, industries have been incentivized to implement advanced technologies to increase efficiency. However, recent disruptive events have highlighted the fragility of supply chains leading the European Commission to update the Industry 4.0 goals.

In particular, supply chain resilience (SCRes) has attracted significant interest from practitioners and researchers. According to the literature, one possibility to obtain SCRes is exploiting artificial intelligence (AI) tools. Indeed, AI can help increase supply chain understanding [3] as machine learning and deep learning models can proactively forecast supply chain risk [4]. However, even if a vast corpus of the literature qualitatively tells these tools' general potential, further studies investigating how to design and exploit these technologies are necessary. Supply chains are subject to many risks, and not enough knowledge about the proper design of machine learning-based approaches for proactively managing each risk has yet been produced.

According to [5], supply chain risks can be distinguished into disruptions and operational risks. While the formers refer to major disruptions caused by natural disasters, wars, economic crises etc., the latter refer to inherent uncertainties related to demand, supply, cost, etc. Furthermore, operational risks have been deeper detailed in [6] into quality risks, capacity/inventory risks, supply risks, demand risks, information flow risks, transportation risks, commodity price fluctuation risks, exchange rate risks, credit risks, environmental risks, and reputation risks.

Among these, supply risks, defined as the risks from upstream operations associated with suppliers and their supply network, are particularly relevant in the automotive sector. Here, companies usually rely on many suppliers, and as a result, little deviance from each supplier's planned behavior can seriously affect them due to the multiplier effect of the broad supplier base.

In this perspective, a common under-investigated but relevant supply risk that can seriously affect the regular production flow comes from partial shipments. To avoid companies' material shortages, suppliers usually split the planned order into multiple deliveries whose overall quantity recreates the entire order. However, although these partial shipments can be helpful for downstream companies to avoid stock out, they generate extra work for the materials acceptance department, which, if not balanced with a proper workforce planning strategy, can easily lead to bottlenecks and delays.

According to the literature investigated in Sect. 20.2, although the problem's relevance, no predictive approaches for supply chain risk generated from suppliers' partial shipments have been developed. This paper thus proposes a new approach based on ARIMAX model for solving the problem. Furthermore, to study the effectiveness of the proposed approach, the following research questions (RQs) have been investigated:

1. *Which performance can the proposed approach achieve in a real case study?*

2. *What are the advantages of the proposed approach regarding time and accuracy compared to other widely adopted forecasting approaches?*
3. *Which are the advantages of the proposed approach when considering different forecasting horizons?*

In this perspective, the main contribution proposed in this work is thus twofold:

- This paper is the first to present a new data-driven approach for predicting supply chain risk related to partial supplier shipments.
- The performance of the proposed approach has been investigated in a real case study.

The rest of the paper is organized as follows: Sect. 20.2 reviews the literature. Section 20.3 presents the new proposed approach, the procedure adopted for testing the performance of the proposed approach, and the data related to the case study on which it has been tested. Section 20.4 presents the result of applying the proposed approach to the case study. In conclusion, Sect. 20.5 discusses the results, its limits, and future research directions.

20.2 Literature Review

Researchers have proposed different types of approaches to deal with operational risks. According to the classification provided by ref. [7, 8], these approaches can be distinguished into predictive and prescriptive. While predictive approaches aim to forecast incumbent risks, prescriptive ones aim to find the best action to take to deal with risks.

Predictive approaches for supply risks have been primarily developed to forecast supplier delivery delays and purchasing costs. Reference [9] proposed a machine learning approach to predict suppliers' delivery punctuality risks to support a resilient supplier selection procedure. For the same problem, the relevance of domain knowledge and features engineering to produce better prediction has been investigated instead by ref. [10]. Reference [11] analyzed the trade-off between performance and interpretability when choosing the best model to solve the delivery delay prediction problem. External data have been instead adopted for the first time by ref. [12] to increase the prediction accuracy of delivery delays prediction models. Lastly, two other innovative points of view on delivery delay prediction have been presented by ref. [13, 14]. In the former, through a federated learning approach, data from different industries have been joined to create better forecasts while preserving company privacy. In the latter, instead, the delivery delay problem has been formulated for the first time as a regression problem where the prediction objective has become the exact amount of delays each supplier would have reported. In conclusion, [15] proposed a predictive approach for supplier cost risk estimation.

However, although several predictive works have been formulated for supply risk, only prescriptive approaches can be found for partial deliveries. In [16], a series of

Table 20.1 Literature review summary

Paper	Supply risk		Approach type	
	Others	Partial Shipment	Predict	Prescript
[9]	X		X	
[10]	X		X	
[11]	X		X	
[12]	X			
[13]	X		X	
[15]	X		X	
[14]	X		X	
[16]		X		X
[17]		X		X
This paper		X	X	

simulations have been conducted to investigate different partial shipment strategies, while in [17], two optimization models for partial shipment have been formulated, and two heuristic procedures for solving them have been proposed.

According to Table 20.1, a clear gap can be thus found in the literature. While predictive approaches for delivery and price risks have been widely proposed in the supply risks-related literature, only prescriptive models have been formulated to deal with partial shipments.

20.3 Materials and Methods

In this section, the proposed data-driven approach is described. Afterward, the case study on which the proposed approach has been tested, and the experimental setup followed to test the proposed approach is illustrated.

20.3.1 Proposed Approach

The approach developed to predict supply chain risk related to supplier's partial shipments comprises four steps, as illustrated in Fig. 20.1.

In the first step, the *data collection step*, which aims to gather and store the information required to build a predictive model in a database, two different data need to be stored in a database every day:

1. The actual number of different components received every day by the company.
2. The number of different components the company expects to receive every day due to the planned orders sent to each supplier for the coming days.

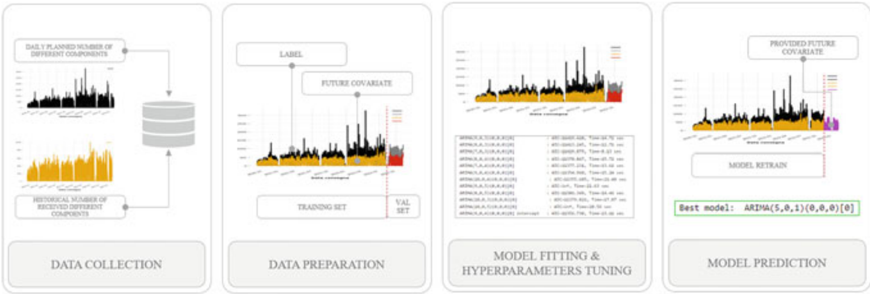

Fig. 20.1 Data-driven proposed approach

These data would report the same value if no partial shipment occurred during the day. Otherwise, the actual amount of daily shipments received would result in a higher value due to the increase of shipments produced by partial shipments.

In the second step, the *data preparation step,* data gathered in the *data collection step* need to be processed in order to be used as input for building a predictive model. First, data need to be split into the label (i.e., the variable to predict) and future covariates (i.e., variables whose future values are known and that help to predict the future value of the label). To this end, the actual number of components received every day by the company is classified as the label. On the contrary, the number of different components the company expects to receive every day due to the planned orders sent to each supplier for the coming days is considered the future covariate. Afterward, the historical data collected for the future covariate and the label are split into two consecutive temporal sets: the training set and the validation set.

The predictive model is built in the third step: the *model fitting and hyperparameters tuning step.* A general ARIMAX model is adopted for this step. An ARIMAX model is an extension of the ARIMA model [18], where predictions of the future value of the label are generated considering both its historical values and the values assumed by the future covariates. The ARIMAX model can be used both for stationary and nonstationary time series. When the time series is stationary, it is possible to refer to the ARIMAX model as ARMAX. A general ARMAX model with a single covariate can be formulated as follow:

$$y_t = \beta_0 + \beta_1 y_{t-1} + \ldots + \beta_p y_{t-p} + \emptyset_1 \varepsilon_{t-1} + \ldots + \emptyset_q \varepsilon_{t-q} + \varepsilon_t + \theta_1 X_{1t} \quad (20.1)$$

Here, β_i is the coefficient of the autoregressive part, y_t is the value of the label at time t, p is the order of the autoregressive process, $\emptyset_{\mathrm{i}}$ represents the coefficient of the moving average part, ε_t is the residual error at time t, and q is the order of the moving average component. Lastly θ_1 is the coefficient of the covariate X_1 and $X_{1\mathrm{t}}$ is the value of the covariate X_1 at the time instant t.

According to the general formulation of an ARMAX model, different values of the parameters and hyperparameters of the ARIMAX model need to be defined. Therefore, in the *model fitting and hyperparameters tuning step*, different parameters

Table 20.2 Data summary

Statistic	Label	Future Covariate
Mean	502	283
Std Deviation	429	223
Min	0	0
Max	3285	997

and hyperparameters need to be tested to identify those values that can minimize the prediction error between the forecast produced by the model and the historical value reported in the validation set. In particular, the value of the coefficient β_i, $\emptyset_{\mathrm{i}}$, and θ_1 is directly obtained when fitting the model with historical data from the training set, while to find the best value of the hyperparameter p and q and to asses if the time series is stationary or not, the procedure described in [19] is adopted.

In conclusion, in the *model prediction step*, the model with the selected hyperparameters is fitted on the complete historical data composed by both the training and the validation set. Afterward, the future covariate's daily values are passed to the model, which will predict the daily number of components the company will receive.

20.3.2 Case Study

Real data from an Italian Automotive company have been used to test the proposed approach. The actual number of different components received every day by the company (label) and the number of different components the company expects to receive every day due to the planned orders sent to each supplier for the coming days (future covariate) have been collected for 891 days. Table 20.2 reports a summary of the collected data.

20.3.3 Experimental Setup

The following experimental setup has been followed to assess the performance of the proposed approach in the illustrated case study and to provide answers to the RQs introduced in Sect. 20.1.

First, the historically collected data were split into three consecutive temporal subsets. Following a widely adopted practice in literature, the first 80% has been used as the training set, the second 10% of data has been used as the validation set, and the last 10% has been used as the test set. The training and the validation set have been used according to Sect. 20.3.1 to build the model, while the new test set has been used to evaluate the proposed approach. In particular, two dimensions have been chosen to evaluate the performance of the proposed approach. The first dimension has been the time required for tuning the hyperparameters of the model.

On the other hand, the second dimension has been the prediction accuracy reported by the proposed approach on the test set. In particular, the prediction accuracy has been measured in terms of mean absolute error (MAE) and root mean squared error (RMSE) computed as in [20]. Furthermore, the adjusted mean absolute percentage error (AMAPE), defined as the ratio between the MAE and the mean value of data, has been adopted to express the accuracy in percentage terms.

Afterward, four widely adopted forecasting approaches have been built to answer RQ2. The first naïve forecasting approach (NAÏVE) has assumed the actual number of different components the company will receive for the coming days to be equal to the same value reported by the company for the previous day. In the second approach, an ARIMA model fitted only with the historical value of the label has been used (ARIMA). Lastly, in the third and fourth approach, an LSTM model [21] has been fitted first only with the historical value of the label (LSTM_UNIV) and then with both the historical value of the label and the future covariates (LSTM_MULTIV).

The hyperparameters of the ARIMA have been chosen following the same procedure described in Sect. 20.3.1. On the other hand, for both the LSTM_UNIV and the LSTM_MULTIV, the label and the future covariate have been normalized according to a MinMax normalization procedure [22]. Afterward, a Bayesian optimization procedure [23] has been used to find the best hyperparameters value for the two LSTM models. In particular, the hyperparameters that have been the object of the optimization have been the number of hidden neurons, the length of the sequence passed as input, and the number of epochs for which the model is trained. According to Sect. 20.3.1, the values of the three hyperparameters that minimize the error on the validation set have been used for the model prediction step. The optimal value of the three hyperparameters has been searched, respectively, in the range [10, 500], [1, 100], and [0, 500]. Furthermore, the hyperparameters tuning step have been limited in time to 7200 s.

In conclusion, to answer RQ3, the proposed approach and the other four approaches have been tested on three different forecasting horizons: a 1-step ahead daily forecast, a 7-step ahead daily forecast, and a 31-step ahead daily forecast.

20.4 Results

In this section, the results obtained testing the proposed on the case study described in Sect. 3.2 are presented to answer the RQs introduced in Sect. 20.1.

According to Fig. 20.2, the proposed approach has demonstrated good forecasting performance reporting an AMAPE value of 17%. Furthermore, the comparison between the proposed approach and other widely adopted models has highlighted its superior performance. A reduction of 74,7%, 68,6%, and 66,5% in terms of MAE has been found when comparing the model with the NAIVE model, the ARIMA model, and the LSTM_UNIV model. On the other hand, the comparison between the proposed approach and an approach based on the LSTM_MULTIV model has

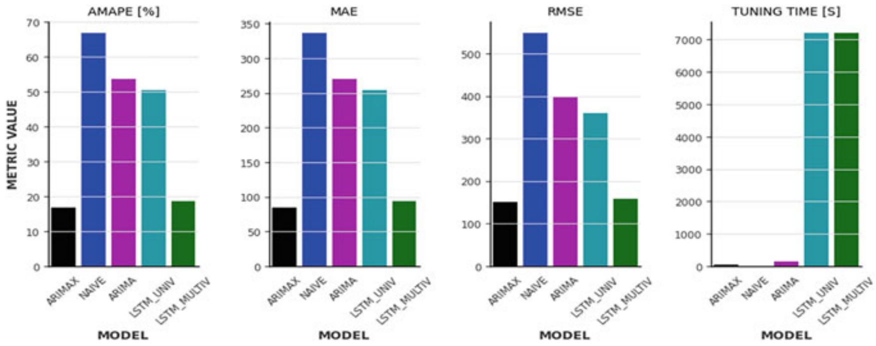

Fig. 20.2 Time and accuracy comparison for one day ahead forecasting

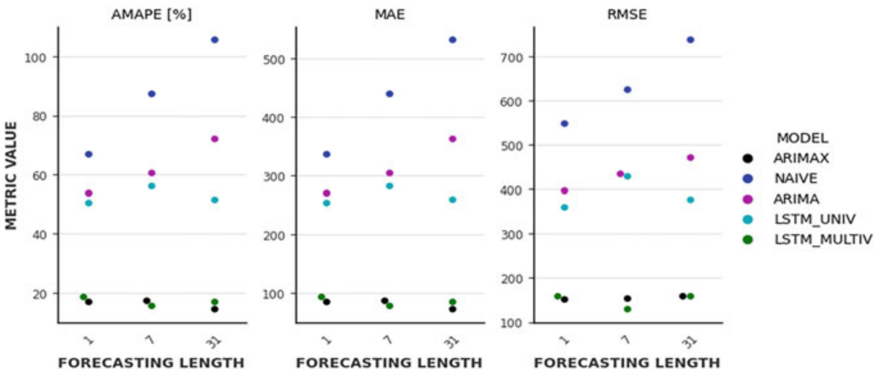

Fig. 20.3 Accuracy comparison with different forecasting lengths

revealed an improvement of 9,1% in terms of MAE and a significant improvement of 99,4% in terms of time required to tune the model.

Furthermore, according to Fig. 20.3, the proposed approach has reported more stable performances when considering different forecasting horizons. Indeed, the accuracy metrics of the predictive approaches based on the NAIVE and ARIMA models worsen with the forecasting horizon. On the contrary, the accuracy performance of the proposed approach remains stable with the increase of the forecast length.

20.5 Discussions and Conclusions

Partial shipments are a widespread procedure in the automotive sector where suppliers, to accomplish companies' necessities to avoid stock out, split the delivery of purchased orders into multiple smaller deliveries. However, although this practice can provide benefits, it also represents an operational risk as it increases the material acceptance department's workload, leading to possible bottlenecks and delays.

In this paper, due to the relevance of the problem and the lack of predictive approaches for managing partial shipment in the literature, a new approach based on the ARIMAX model has been proposed. Experiments conducted on a real case study of an Italian automotive company have shown the ability of the proposed approach to reach good forecasting performance (i.e., an AMAPE value of 17%). Furthermore, comparisons with other univariate models have highlighted the advantages of formulating the problem in a multivariate fashion. Indeed, a reduction of 66,5% in terms of MAE has been found comparing it to the best univariate model (LSTM_UNIV). Lastly, both the proposed approach and a different approach based on a multivariate LSTM model (LSTM_MULTIV) have demonstrated stable accuracy performance with the increase of the forecast horizon. Indeed, while the accuracy performance of ARIMA has increased from an AMAPE of 53% to 72% when increasing the forecasting length from one day to 31 days, the accuracy of the multivariate ones has remained stable. In conclusion, the LSTM_MULTIV and the ARIMAX model have reported comparable accuracy performance. However, a clear advantage in tuning time has been noticed in adopting the ARIMAX model, which requires 99,6% less time than the LSTM_MULTIV model to be tuned.

However, the results obtained in this work are subject to three main limitations. First, the proposed approach has been tested on only one case study. Furthermore, not all the existing possible forecasting models have been compared to the proposed ones. Lastly, the research on the best hyperparameters for the LSTM models has been limited within the time of 2 h.

According to the observed limitation, further study can be thus directed in testing the proposed approach on multiple case studies, comparing the performance obtained by the ARIMAX models with other models, and extending the tuning time of the LSTM model. Furthermore, testing the proposed approach in dealing with other temporal aggregations (i.e., weekly or monthly forecasts) could be another future direction.

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Chapter 21
Energy Network Optimization Model for Supporting Generation Expansion Planning and Grid Design

Cristian Cafarella, Marco Bortolini, Matteo Gabellini, Francesco Gabriele Galizia, and Valentina Ventura

Abstract Generation and transmission expansion planning (GEP and TEP) consists of finding the optimal long-term energy plan for the construction of new generation and transmission capacity. Typically, it deals with solving a large-scale, nonlinear discrete and dynamic optimization problem with complex constraints and a high level of uncertainty. The current literature continuously looks for quantitative multi-perspective strategies and models, including and best balancing such issues. This paper focuses on the GEP and TEP of large-scale energy systems with a high share of renewables. Particularly, this paper presents and applies an optimization model for GEP and TEP. The general model formulation does not focus on a specific geographical area. However, the model can be adapted and applied to several specific contexts. The model outcomes involve the optimal generation mix planning, the analysis of energy flows, and the mapping of critical energy areas. Finally, the model is applied to a case study, based on the Italian context, to test and validate it.

21.1 Introduction and Literature Review

The generation and transmission expansion planning (GEP and TEP) represents for academia and decision-makers in the energy sector one of the most discussed topics, especially to achieve the emission reduction objectives. GEP and TEP are complex tasks, combining techno-economic, financial, spatial, and environmental aspects. Several models, strategies, and techniques are developed to GEP and TEP, applying different methodological approaches [1–3]. Table 21.1 shows a preliminarily classification of the relevant literature on GEP and TEP. The review shows that the single-objective methods often integrate environmental aspects as constraints or external costs, while the multi-objective formulations consider them as one of

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Table 21.1 Literature contributions classification

Optimization KPI			Problem formulation		Solving method		Planning procedure	Case study/ application	References
C	E	SR	SO	MO	S	A/H			
✔	✔		✔			✔	GEP	Thailand	[4]
✔		✔		✔	✔		GEP	Portugal	[5]
✔	✔		✔		✔		GEP	China	[6]
✔	✔	✔		✔	✔		GEP	Test system	[7]
✔			✔		✔		GEP, TEP	–	[8]
✔		✔	✔			✔	GEP	Test system	[9]
✔	✔		✔		✔		GEP	United states	[10]
✔			✔		✔		GEP	Japan	[11]
✔	✔			✔	✔		GEP, TEP	Test system	[12]
✔	✔		✔		✔		GEP, TEP	Italy	This Paper

C Costs, *E* Emissions, *SR* System Reliability, *SO* Single-Objective, *MO* Multi-Objective, *S* Solver, *A/H* Algorithm/Heuristics

the objectives. Furthermore, the review emphasizes that GEP and TEP optimization approaches offer significant potential for the simulation of national or regional power systems, providing practical and realistic information for decision-makers. This paper attempts to contribute to this research stream introducing and applying a mixed-integer linear programming (MILP) optimization cost model for the GEP and TEP. The model formulation considers environmental aspects and promotes a distributed energy production to minimize the transmission losses and costs. The case study, based on the Italian context, considers a major set of power plants and connections that currently operate in Italy, as well as the option to increase the energy producers through a set of new wind and solar plants. In addition, reliable forecasts on carbon tax, fuel costs, and energy demand profiles are included to best represent the current and future Italian energy scenario.

According to this, the remainder of the paper is organized as follows: the next Sect. 21.2 details the MILP model formulation, while Sect. 21.3 describes the case study used to validate the model. In Sect. 21.4, the results of the model application are reported and discussed. Finally, Sect. 21.5 concludes the paper with some remarks and opportunities for future research.

21.2 Methodology

In Bortolini et al. [8], a MILP cost model for the energy mix planning and the electrical grid management was presented. The formulation proposed in [8], as well as in several other studies [1–3], groups all the energy producers, nodes, and consumers belonging to the same geographical area and considers them as a single entity in terms of energy flows origin, destination, and dispatching. Instead, this paper proposes a model formulation, where each demand point is supplied independently and all the energy flows are between independent couples of entities, i.e., producers, dispatching nodes, and consumers. The proposed model belongs to the class of location allocation problems (LAP) and takes into account a three-level electrical grid structure. Specifically, electricity flows from power plants at the production level to the nodes of the electrical grid at the dispatching level and, ultimately, reaches the demand areas at the consumption level. The grid connections are divided into six subsets, three for the existing connections (EC) and three for the future connections (FC): plant-node (EC_1 and FC_1), node–node (EC_2 and FC_2), and node-consumer (EC_3 and FC_3). The main features of the LAP model are described in the following. In particular, Table 21.2 shows the entities, indices, and parameters of the model, while Table 21.3 presents the decision variables.

The objective function of the LAP model, expressed in (21.1), minimizes the sum of the variable costs related to the energy production and distribution, the plant and grid connection investment, fix and decommissioning costs, and the energy source costs for the energy production, e.g., the fuel costs and the carbon tax.

$$
\begin{aligned}
\phi_{LAP} = & \sum_{t \epsilon EP} i_t \cdot cp_t \cdot \alpha_{e_t} + \sum_{s \epsilon FP} \sum_{y \epsilon YS} i_s \cdot Ic_{sy} \cdot \alpha_y + \sum_{k_1 \epsilon EC_1} i_{k_1} \cdot cp_{k_1} \cdot \alpha_{e_{k_1}} \\
& + \sum_{m_1 \epsilon FC_1} \sum_{y \epsilon YS} i_{m_1} \cdot Ic_{m_1 y} \cdot \alpha_y + \sum_{k_2 \epsilon EC_2} i_{k_2} \cdot cp_{k_2} \cdot \alpha_{e_{k_2}} \\
& + \sum_{m_2 \epsilon FC_2} \sum_{y \epsilon YS} i_{m_2} \cdot Ic_{m_2 y} \cdot \alpha_y + \sum_{k_3 \epsilon EC_3} i_{k_3} \cdot cp_{k_3} \cdot \alpha_{e_{k_3}} \\
& + \sum_{m_3 \epsilon FC_3} \sum_{y \epsilon YS} i_{m_3} \cdot Ic_{m_3 y} \cdot \alpha_y + \sum_{t \epsilon EP} \sum_{\substack{y \epsilon YS \\ e_t \le y \le e_t + lt_t}} f_t \cdot cp_t \cdot \alpha_y \\
& + \sum_{s \epsilon FP} \sum_{y \epsilon YS} f_s \cdot \sum_{\substack{y_1 \epsilon YS \\ y \le y_1}} Ic_{sy_1} \cdot \alpha_y + \sum_{k_1 \epsilon EC_1} \sum_{\substack{y \epsilon YS \\ e_{k_1} \le y \le e_{k_1} + It_{k_1}}} f_{k_1} \cdot cp_{k_1} \cdot \alpha_y \\
& + \sum_{m_1 \epsilon FC_1} \sum_{y \epsilon YS} f_{m_1} \cdot \sum_{\substack{y_1 \epsilon YS \\ y \le y_1}} Ic_{m_1 y_1} \cdot \alpha_y + \sum_{k_2 \epsilon EC_2} \sum_{\substack{y \epsilon YS \\ e_{k_2} \le y \le e_{k_2} + It_{k_2}}} f_{k_2} \cdot cp_{k_2} \cdot \alpha_y \\
& + \sum_{m_2 \epsilon FC_2} \sum_{y \epsilon YS} f_{m_2} \cdot \sum_{\substack{y_1 \epsilon YS \\ y \le y_1}} Ic_{m_2 y_1} \cdot \alpha_y + \sum_{k_3 \epsilon EC_3} \sum_{\substack{y \epsilon YS \\ e_{k_3} \le y \le e_{k_3} + It_{k_3}}} f_{k_3} \cdot cp_{k_3} \cdot \alpha_y \\
& + \sum_{m_3 \epsilon FC_3} \sum_{y \epsilon YS} f_{m_3} \cdot \sum_{\substack{y_1 \epsilon YS \\ y \le y_1}} Ic_{m_3 y_1} \cdot \alpha_y + \sum_{t \epsilon EP} \sum_{h \epsilon TP} v_t \cdot En_{th} \cdot \alpha_{yr_h} \\
& + \sum_{s \epsilon FP} \sum_{h \epsilon TP} v_s \cdot En_{sh} \cdot \alpha_{yr_h} + \sum_{k_1 \epsilon EC_1} \sum_{h \epsilon TP} v_{k_1} \cdot En_{k_1 h} \cdot \alpha_{yr_h}
\end{aligned}
$$

Table 21.2 Sets, indices, and parameters of the LAP model

Index: t	*Set: existing plants* (EP)		*Index*: s	*Set: future plants* (FP)	
co_t	Plant area	in AR	co_s	Plant area	in AR
st_t	Source type	in SO	st_s	Source type	in SO
cp_t	Installed capacity	MW	cp_s	Installed capacity	MW
η_t	Composite outage	in [0,1]	η_s	Composite outage	in [0,1]
e_t	Earliest online year	in YS	e_s	Earliest online year	in YS
lt_t	Plant lifetime	in years	lt_s	Plant lifetime	in years
χ_t	Capacity factor	in [0,1]	χ_s	Capacity factor	in [0,1]
i_t	Investment cost	€/MW	i_s	Investment cost	€/MW
f_t	Annual fix cost	€/MW	f_s	Annual fix cost	€/MW
v_t	Variable cost	€/MWh	v_s	Variable cost	€/MWh
u_t	Decommissioning	€/MW	u_s	Decommissioning	€/MW
b_t	Base-load plant	Boolean	b_s	Base-load plant	Boolean
Index: k	*Set: existing connections* (EC)		*Index*: m	*Set: future connections* (FC)	
cp_k	Installed capacity	MW	cp_m	Installed capacity	MW
η_k	Transmission losses	in [0,1]	η_m	Transmission losses	in [0,1]
e_k	Earliest online year	in YS	e_m	Earliest online year	in YS
lt_k	Line lifetime	in years	lt_m	Line lifetime	in years
i_k	Investment cost	€/MW	i_m	Investment cost	€/MW
f_k	Annual fix cost	€/MW	f_m	Annual fix cost	€/MW
v_k	Variable cost	€/MWh	v_m	Variable cost	€/MWh
u_k	Decommissioning	€/MW	u_m	Decommissioning	€/MW
Index: p	*Set: demand points* (DP)		*Index*: j	*Set: sources* (SO)	
co_p	Demand point area	in AR	r_j	Renewable	Boolean
d_{ph}	Demand entity	MWh h in TP	c_{jy}	Source cost	€/MWh y in YS
Index: h	*Set: time points* (TP)		*Index*: y	*Set: Years* (YS)	
yr_h	Year	in YS	α_y	Discount factor	R^+
dr_h	Time point duration	hours	φ_{ay}	% from renewables	in [0,1] a in AR
Index: a	*Set: geographical areas* (AR)		*Index*: n	*Set: dispatching node* (DN)	

$$+\sum_{m_1\epsilon FC_1}\sum_{h\epsilon TP} v_{m_1}\cdot En_{m_1h}\cdot\alpha_{yr_h}+\sum_{k_2\epsilon EC_2}\sum_{h\epsilon TP} v_{k_2}\cdot En_{k_2h}\cdot\alpha_{yr_h}$$
$$+\sum_{m_2\epsilon FC_2}\sum_{h\epsilon TP} v_{m_2}\cdot En_{m_2h}\cdot\alpha_{yr_h}+\sum_{k_3\epsilon EC_3}\sum_{h\epsilon TP} v_{k_3}\cdot En_{k_3h}\cdot\alpha_{yr_h}$$
$$+\sum_{m_3\epsilon FC_3}\sum_{h\epsilon TP} v_{m_3}\cdot En_{m_3h}\cdot\alpha_{yr_h}+\sum_{t\epsilon EP} u_t\cdot cp_t\cdot\alpha_{e_{t+lt_t+1}}$$
$$+\sum_{s\epsilon FP} u_s\cdot\sum_{y\epsilon YS} Ic_{sy}\cdot\alpha_{e_{s+lt_s+1}}$$

Table 21.3 Decisional variables of the LAP model

Decisional variables		
Ic_{sy}	FP installed capacity	in MWh, s in FP, y in YS
En_{th}	EP produced energy	in MWh, t in EP, h in TP
En_{sh}	FP produced energy	in MWh, s in FP, h in TP
B_{th}	EP activation	in {0,1}, t in EP, h in TP
B_{sh}	FP activation	in {0,1}, s in FP, h in TP
Ic_{m_1y}	FC plant-node installed capacity	in MW, m_1 in FC_1, y in YS
Ic_{m_2y}	FC node–node installed capacity	in MW, m_2 in FC_2, y in YS
Ic_{m_3y}	FC node-demand point installed capacity	in MW, m_3 in FC_3, y in YS
En_{k_1h}	EC plant-node dispatched energy	in MWh, k_1 in EC_1, h in TP
En_{k_2h}	EC node–node dispatched energy	in MWh, k_2 in EC_2, h in TP
En_{k_3h}	EC node-demand point dispatched energy	in MWh, k_3 in EC_3, h in TP
En_{m_1h}	FC plant-node dispatched energy	in MWh, m_1 in FC_1, h in TP
En_{m_2h}	FC node–node dispatched energy	in MWh, m_2 in FC_2, h in TP
En_{m_3h}	FC node-demand point dispatched energy	in MWh, m_3 in FC_3, h in TP

$$+\sum_{k_1\epsilon EC_1} u_{k_1}\cdot cp_{k_1}\cdot \alpha_{e_{k_1+lt_{k_1}+1}} + \sum_{m_1\epsilon FC_1} u_{m_1}\cdot \sum_{y\epsilon YS} Ic_{m_1y}\cdot \alpha_{e_{m_1+lt_{m_1}+1}}$$
$$+\sum_{k_2\epsilon EC_2} u_{k_2}\cdot cp_{k_2}\cdot \alpha_{e_{k_2+lt_{k_2}+1}} + \sum_{m_2\epsilon FC_2} u_{m_2}\cdot \sum_{y\epsilon YS} Ic_{m_2y}\cdot \alpha_{e_{m_2+lt_{m_2}+1}}$$
$$+\sum_{k_3\epsilon EC_3} u_{k_3}\cdot cp_{k_3}\cdot \alpha_{e_{k_3+lt_{k_3}+1}} + \sum_{m_3\epsilon FC_3} u_{m_3}\cdot \sum_{y\epsilon YS} Ic_{m_3y}\cdot \alpha_{e_{m_3+lt_{m_3}+1}}$$
$$+\sum_{j\epsilon SO}\sum_{y\epsilon YS} c_{jy}\cdot\left(\sum_{\substack{t\epsilon EP\\ st_t=j}}\sum_{\substack{h\epsilon TP\\ yr_h=y}} En_{th} + \sum_{\substack{s\epsilon FP\\ st_s=j}}\sum_{\substack{h\epsilon TP\\ yr_h=y}} En_{sh}\right)\cdot\alpha_y \tag{21.1}$$

The following constraints complete the proposed model and ensure its feasibility.

$$\sum_{\substack{k_3=\left(n^f,p^t\right)\in EC_3\\ p^t=p}} En_{k_3h}\cdot(1-\eta_{k3}) + \sum_{\substack{m_3=\left(n^f,p^t\right)\in EC_3\\ p^t=p}} En_{m_3h}\cdot(1-\eta_3) = d_{ph}$$

$$p\in DP, h\in TP \tag{21.2}$$

$$En_{th} = \sum_{\substack{k_1 = \left(t^f, n^t\right) \in EC_1 \\ t^f = t}} En_{k_1 h} \quad t \in EP, h \in TP \tag{21.3}$$

$$En_{sh} = \sum_{\substack{m_1 = \left(s^f, n^t\right) \in FC_1 \\ s^f = s}} En_{m_1 h} \quad s \in FP, h \in TP \tag{21.4}$$

$$\begin{aligned} \sum_{\substack{k_1 = \left(t^f, n^t\right) \in EC_1 \\ n^t = n}} En_{k_1 h} \cdot \left(1 - \eta_{k_1}\right) + & \sum_{\substack{m_1 = \left(s^f, n^t\right) \in FC_1 \\ n^t = n}} En_{m_1 h} \cdot \left(1 - \eta_{m_1}\right) \\ & + \sum_{\substack{k_2 = \left(n^f, n^t\right) \in EC_2 \\ n^t = n \wedge n^f \neq n}} En_{k_2 h} \cdot \left(1 - \eta_{k_2}\right) \\ & + \sum_{\substack{m_2 = \left(n^f, n^t\right) \in FC_2 \\ n^t = n \wedge n^f \neq n}} En_{m_2 h} \cdot \left(1 - \eta_{m_2}\right) \\ & = \sum_{\substack{k_2 = \left(n^f, n^t\right) \in EC_2 \\ n^t = n \wedge n^f \neq n}} En_{k_2 h} \\ & + \sum_{\substack{m_2 = \left(n^f, n^t\right) \in FC_2 \\ n^t = n \wedge n^f \neq n}} En_{m_2 h} \\ & + \sum_{\substack{k_3 = \left(n^f, p^t\right) \in EC_3 \\ n^f = n}} En_{k_3 h} \\ & + \sum_{\substack{m_3 = \left(n^f, p^t\right) \in FC_3 \\ n^f = n}} En_{m_3 h} \\ & n \in DN, h \in TP \end{aligned} \tag{21.5}$$

$$\sum_{\substack{t \in EP \\ r_{st_t=1}}} \sum_{\substack{h \in TP \\ yr_h = y}} E_{n_{th}} + \sum_{\substack{s \in FP \\ r_{st_s=1}}} \sum_{\substack{h \in TP \\ yr_h = y}} E_{n_{sh}} \geq \varphi_{ay}$$

$$\cdot\left(\sum_{t\in EP}\sum_{\substack{h\in TP\\ yr_h=y}} E_{n_{th}}+\sum_{s\in FP}\sum_{\substack{h\in TP\\ yr_h=y}} E_{n_{sh}}\right)\quad a\in AR, y\in YS \tag{21.6}$$

$$\sum_{y\in YS} Ic_{sy}\le cp_s \quad s\in FP \tag{21.7}$$

$$Ic_{sy}=0 \quad s\varepsilon FP, y\in YS\wedge(y<e_s\vee y>e_s+lt_s) \tag{21.8}$$

$$\sum_{y\in YS} Ic_{m_1y}\le cp_{m_1} \quad m_1\in FC_1 \tag{21.9}$$

$$Ic_{m_1y}=0 \quad m_1\in FC_1, y\in YS\wedge\left(y<e_{m_1}\vee y>e_{m_1}+lt_{m_1}\right) \tag{21.10}$$

$$\sum_{y\in YS} Ic_{m_2y}\le cp_{m_2} \quad m_2\in FC_2 \tag{21.11}$$

$$Ic_{m_2y}=0 \quad m_2\in FC_2, y\in YS\wedge\left(y<e_{m_2}\vee y>e_{m_2}+lt_{m_2}\right) \tag{21.12}$$

$$\sum_{y\in YS} Ic_{m_3y}\le cp_{m_3} \quad m_3\in FC_3 \tag{21.13}$$

$$Ic_{m_3y}=0 \quad m_3\in FC_3, y\in YS\wedge\left(y<e_{m_3}\vee y>e_{m_3}+lt_{m_3}\right) \tag{21.14}$$

$$En_{th}=0 \quad t\in EP, h\in TP\wedge(yr_h<e_t\vee yr_h>e_t+lt_t) \tag{21.15}$$

$$En_{th}=cp_t\cdot \mathrm{d}r_h\cdot\chi_t\cdot B_{th} \quad t\in EP\wedge b_t=1, h\in TP\wedge(e_t\le yr_h\le e_t+lt_t) \tag{21.16}$$

$$En_{th}\le cp_t\cdot \mathrm{d}r_h\cdot\chi_t\cdot B_{th} \quad t\in EP\wedge b_t=0, h\in TP\wedge(e_t\le yr_h\le e_t+lt_t) \tag{21.17}$$

$$En_{sh}=0 \quad s\in FP, h\in TP\wedge(yr_h<e_s\vee yr_h>e_s+lt_s) \tag{21.18}$$

$$En_{sh}=\sum_{\substack{y\in YS\\ y<yr_h}} Ic_{sy}\cdot dr_h\cdot\chi_s\cdot B_{sh}$$
$$s\in FP\wedge b_s=1, h\in TP\wedge(e_s\le yr_h\le e_s+lt_s) \tag{21.19}$$

$$En_{sh} \leq \sum_{\substack{y \in YS \\ y < yr_h}} Ic_{sy} \cdot dr_h \cdot \chi_s \cdot B_{sh}$$

$$s \in FP \wedge b_s = 0, h \in TP \wedge (e_s \leq yr_h \leq e_s + lt_s) \tag{21.20}$$

$$En_{k_1h} = 0 \quad k_1 \in EC_1, h \in TP \wedge \left(yr_h < e_{k_1} \vee yr_h > e_{k_1} + lt_{k_1}\right) \tag{21.21}$$

$$En_{k_1h} \leq cp_{k_1} \cdot \mathrm{d}r_h \cdot \left(1 - \eta_{k_1}\right) \quad k_1 \in EC_1, h \in TP \wedge \left(e_{k_1} \leq yr_h \leq e_{k_1} + lt_{k_1}\right) \tag{21.22}$$

$$En_{k_2h} = 0 \quad k_2 \in EC_2, h \in TP \wedge \left(yr_h < e_{k_2} \vee yr_h > e_{k_2} + lt_{k_2}\right) \tag{21.23}$$

$$En_{k_2h} \leq cp_{k_2} \cdot \mathrm{d}r_h \cdot \left(1 - \eta_{k_2}\right) \quad k_2 \in EC_2, h \in TP \wedge \left(e_{k_2} \leq yr_h \leq e_{k_2} + lt_{k_2}\right) \tag{21.24}$$

$$En_{k_3h} = 0 \quad k_3 \in EC_3, h \in TP \wedge \left(yr_h < e_{k_3} \vee yr_h > e_{k_3} + lt_{k_3}\right) \tag{21.25}$$

$$En_{k_3h} \leq cp_{k_3} \cdot \mathrm{d}r_h \cdot \left(1 - \eta_{k_3}\right) \quad k_3 \in EC_3, h \in TP \wedge \left(e_{k_3} \leq yr_h \leq e_{k_3} + lt_{k_3}\right) \tag{21.26}$$

$$En_{m_1h} = 0 \quad m_1 \in FC_1, h \in TP \wedge \left(yr_h < e_{m_1} \vee yr_h > e_{m_1} + lt_{m_1}\right) \tag{21.27}$$

$$En_{m_1h} \leq \sum_{\substack{y \in YS \\ y < yr_h}} Ic_{m_1y} \cdot dr_h \cdot \left(1 - \eta_{m_1}\right)$$

$$m_1 \in FC_1, h \in TP \wedge \left(e_{m_1} \leq yr_h \leq e_{m_1} + lt_{m_1}\right) \tag{21.28}$$

$$En_{m_2h} = 0 m_2 \in FC_2, h \in TP \wedge \left(yr_h < e_{m_2} \vee yr_h > e_{m_2} + lt_{m_2}\right) \tag{21.29}$$

$$En_{m_2h} \leq \sum_{\substack{y \in YS \\ y < yr_h}} Ic_{m_2y} \cdot dr_h \cdot \left(1 - \eta_{m_2}\right)$$

$$m_2 \in FC_2, h \in TP \wedge \left(e_{m_2} \leq yr_h \leq e_{m_2} + lt_{m_2}\right) \tag{21.30}$$

$$En_{m_3h} = 0 \quad m_3 \in FC_3, h \in TP \wedge \left(yr_h < e_{m_3} \vee yr_h > e_{m_3} + lt_{m_3}\right) \tag{21.31}$$

$$En_{m_3h} \leq \sum_{\substack{y \in YS \\ y < yr_h}} Ic_{m_3y} \cdot dr_h \cdot \left(1 - \eta_{m_3}\right)$$

$$m_3 \in FC_3, h \in TP \wedge \left(e_{m_3} \leq yr_h \leq e_{m_3} + lt_{m_3}\right) \tag{21.32}$$

$$Ic_{sy}, En_{th}, En_{sh}, Ic_{m_1y}, Ic_{m_2y}, Ic_{m_3y}, En_{k_1h}, E_{n_{k_2h}}, En_{k_3h},$$
$$En_{m_1h}, En_{m_2h}, En_{m_3h} \geq 0$$

$$s \in FP, y \in YS, t \in EP, h \in TP, m_1 \in FC_1, m_2 \in FC_2,$$
$$m_3 \in FC_3, k_1 \in EC_1, k_2 \in EC_2, k_3 \in EC_3 \tag{21.33}$$

$$B_{th}, B_{sh} bynarys \in FP, t \in EP, h \in TP \tag{21.34}$$

Equation (21.2) imposes the satisfaction of the electricity demand for each demand and time point, while Eqs. (21.3) and (21.4) guarantee that the energy generated by plants is equivalent to the energy distributed via the connections between plants and nodes, for each plant and time point. Equation (21.5) balances the energy flows between the production and dispatching levels, for each dispatching node and time point. Equation (21.6) forces the system to generate a minimum share of electricity from renewable. Equations (21.7)–(21.14) ensure that the installed capacity for each future plant and connection does not exceed the maximum available capacity and set to zero the installed capacity for all the years out of the lifetime. Equations (21.15)–(21.20) limit the production of each power plant according to its technical features and set it to zero out of the plant lifetime. Equations (21.21)–(21.32) ensure that the transmission capacity limits are respected for each connection and set it to zero out of the connection lifetime. The consistence to the non-negative continuous and binary decisional variables is ensured by Eqs. (21.33) and (21.34).

21.3 Case Study Description

Considering a long-term horizon from 2023 to 2040, the proposed model is applied to a case study focusing on the Italian context. The model application considers a significant subset of the power plants and connections currently in operation in Italy, as well as the expected trend in electricity demand until the year 2040. In addition, according to the forecast about the evolution of the total installed capacity in Italy [13], the case study considers the option to increase the energy producers using a set of new wind and solar plants. The input data used to feed the model, i.e., parameters, are partially derived from the case study presented in a previous work of the authors [14]. Particularly, Bortolini et al. [14] present and apply to the Italian context a MILP model to optimizing an existing energy network, in term of best allocation of the energy flows among existing dispatching nodes, with no new plants and connections activation. Hence, to update and extend this case study, additional relevant sources are considered to include the option of increasing the energy producers. The considered power plants dataset has a total installed capacity of 94.34 GW for the EP and of 39 GW for the FP [14–18]. Starting from the data reported by TERNA [19], the capacity factors are derived for the different energy source. Moreover, wind, solar, and biogas capacity are aggregated at the provincial level, covering all 107 Italian provinces. Figure 21.1a and b shows the capacity and the distribution over the Italian territory of the EP and FP, respectively. The investment, fix, and variable costs for the power plants are considered using the Levelized Cost of Energy (LCOE) of the different sources reported in [19]. The carbon tax and fuel costs trends from 2023 to 2040 are included based on [20, 21].

The consumption level comprises 107 DP, i.e., the Italian provinces, and 216 TP, represented by the total number of months from 2023 to 2040. The dispatching level includes 70 DN connected with the EP, FP, DP based on the minimum distance criteria. The transmission losses are computed based on [8, 19]. Finally, further aspects complete the case study, i.e., no minimum renewable level is imposed by setting the φ_{ay} parameter to zero; new production capacity can be installed from the year 2031 onwards; no limitations in connection capacity are considered, and no plants and connections are decommissioned.

The MILP model is written in the AMPL language, and the instance was solved in about 300 s through the commercial Gurobi Optimazer© v.9.5.2 solver. The computational environment consists of a workstation with an Intel® CoreTM i5-8250U CPU @ 1.60 GHz and 8.0GB of RAM.

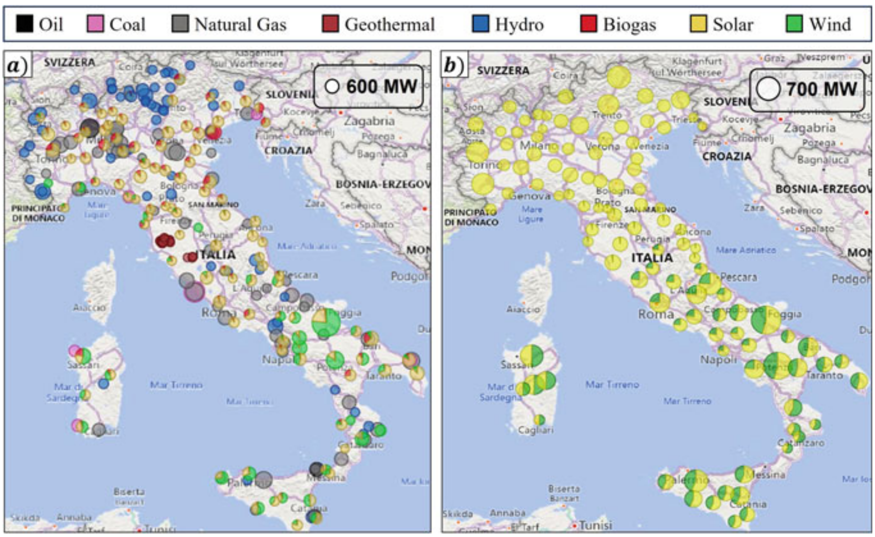

Fig. 21.1 Location and capacity of plants by energy source. **a** Existing plants. **b** Future plants

21.4 Results and Discussion

The application of the proposed model to the case study results in an average LCOE of 110 €/MWh, calculated over the entire time horizon of the study. The main results of the paper are presented and discussed below.

In the model application, it is assumed that the new solar and wind capacity can be installed from the year 2031 onwards. As a result, the entire new available solar and wind capacity, shown in Fig. 21.1b, is installed in the year 2031. From 2023 to 2030, the results show that Italy is still dependent on the fossil fuels for the 57% of its electricity production, where natural gas accounts for 48% of the total. From 2031 to 2040, the installation of the new solar and wind plants significantly increases the shares of renewables in the energy mix to 55%. In this period, solar and wind cover, respectively, the 25% and 12% of the total. Overall, the north of Italy presents the highest production and consumption levels, respectively, 55% and 62% of the total. Lombardy, Emilia-Romagna, and Piedmont together account for more than 40%. In central Italy, the production and consumption levels are very low (15% and 13%). Finally, in the south and the islands the production and consumption levels cover 30% and 25%, respectively.

For the year 2040, in Fig. 21.2a provinces with a significant energy deficit are shown in dark red and those with a significant energy surplus in dark blue. Intermediate values are represented with the shades of the two colors. Figure 21.2b shows the amount of energy flowing through the connections of the Italian high-voltage electricity grid. The color of the line is a function of the amount of energy crossing that connection.

As shown in Fig. 21.2, the Italian high-voltage electrical grid presents a cobweb structure in the north and two parallel north–south energy corridors, namely Tyrrhenian and Adriatic corridors. Within both energy corridors, energy moves from south

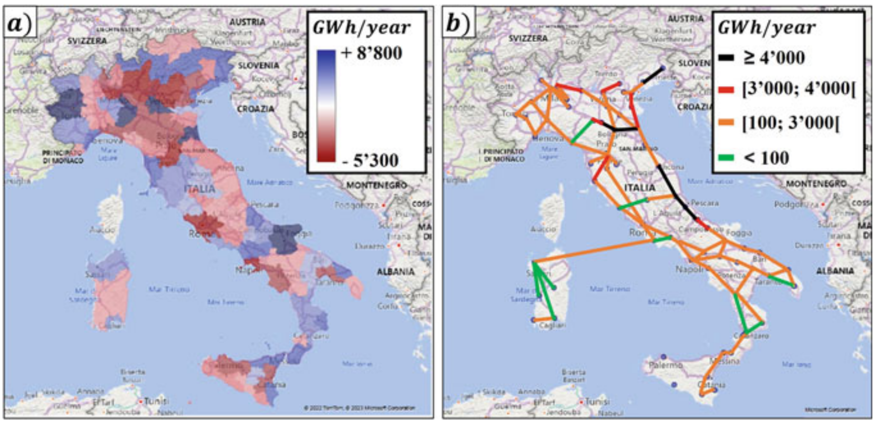

Fig. 21.2 Mapping of critical energy areas and energy flows on the electrical grid for 2040. **a** Energy deficit and surplus by province. **b** Energy flows on high-voltage grid connections

to north to fill the deficits of critical areas. Concerning the islands, energy flows from Sardinia and Sicily toward the Italian peninsula. Overall, provinces with high population densely, low production capacity, and/or energy-intensive industrial districts are in energy deficit and represent the end points of energy flows.

21.5 Conclusions and Future Research

GEP and TEP models rise as accurate tools to support decision-making in addressing issues such as climate change and the development of highly resilient energy networks. In such a context, this paper presents and applies an optimization cost model for GEP and TEP. The problem formulation considers environmental aspect and promotes a distributed production to minimize the transmission losses. The case study, based on the Italian context, considers a major set of power plants and connections currently operating in Italy, as well as the option to increase the energy producers through a set of new wind and solar plants. Moreover, reliable forecast on carbon tax, fuel costs, and energy demand profiles between 2023 and 2040 are included. From 2023 to 2030, the outcomes show that Italy is still dependent on the fossil fuels for the 57% of its electricity production, where natural gas accounts for 48% of the total. From 2031 to 2040, the installation of the new solar and wind plants significantly increases the shares of renewables in the energy mix to 55%. Solar and wind cover, respectively, the 25% and 12% and represent a great opportunity from both economic and environmental point of view. Although in this scenario the share of natural gas in the energy mix decreases to 38% by 2040, it remains the main source for electricity production. In the Italian peninsula, most of the energy demand and production is concentrated in the north of Italy, where energy-intensive industrial districts and large conventional plants are located. Southern Italy, including Sicily and Sardinia, represents the area with the greatest wind and solar energy potential. Hence, as underlined by the paper results, the investment in new wind and solar capacity in the southern Italy, as well as energy transmission from south to north, represent a key element of the future Italian energy scenario.

Future research is oriented toward two directions of development. The first direction involves enhancing the model, by taking into account further significant techno-economic, environmental and social factors with a multi-objective view. The second direction focuses on further model applications to other geographical contexts.

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Chapter 22
A Clustering-Based Algorithm for Product Platform Design in the Mass Customization Era

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Abstract The modern industry is facing the great challenge of meeting the changeable needs of the highly competitive global market, asking for an increasing variety of customized products. To manage the product variety, minimizing time to market and costs, companies started adopting a hybrid production strategy named delayed product differentiation (DPD) through the use of the so-called product platforms. Platforms are sub-systems forming a common structure from which a stream of derivative variants can be efficiently produced. Platforms are typically manufactured and stocked following a Make-to-Stock (MTS) strategy, while the personalization is managed according to a Make-to-Order (MTO) strategy after the arrival of the customers' orders. Most of the existing methods addressing the platform design uses optimization techniques, resulting in high computational complexity to manage the real size of the industrial instances. To support practitioners, this paper proposes a hierarchical clustering algorithm, based on the definition of a new similarity index. The algorithm uses the similarity index to evaluate the production cycle of the variants provided as input and returning a set of product variants' clusters, assigning a platform to each of them. The proposed methodology is applied to an industrial case study to exemplify the management of high-variety production mixes.

22.1 Introduction and Literature Review

In the recent years, the spread of product variety is forcing companies to move from mass production to mass customization (MC) paradigm. Several reasons drive this trend, including the customer demand of new product functions and features, regional requirements, and market segments with peculiar needs and specifications [1]. According to Bortolini et al. [2] product variety positively contributes to expand

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markets and to increase volumes and revenues if proper strategies are adopted at all the stages of the product lifecycle from design to end of life [2, 3]. About the manufacturing phase, traditional production strategies, as Make to Stock (MTS) and Make to Order (MTO), present limitations [4]. Despite MTS allows company to meet the customer orders in short lead times, the wide marketing mixes make this strategy less convenient from the inventory management side. On the contrary, adopting MTO reduces the storage costs but leads to longer order supply time [5]. To join the dual needs of high-variety and low customer lead time, hybrid production strategies are emerging, as the delayed product differentiation (DPD) strategy, which aims at postponing the customization activities using the so-called product platforms [6]. According to the original definition, a product platform is "a set of common components, modules or parts from which a stream of derivative products can efficiently be developed and launched" [7–9]. Platforms are mass produced and stocked in advance following a MTS strategy, managing the final personalization after the order arrival by using a MTO approach.

Recent studies developed optimization models, providing the optimal product platform configuration and the product variant-platform association [10–12], while other considered inventory, demand or production matching [4, 13, 14]. Nevertheless, optimization models may be often unable to solve large real size industrial instances in a reasonable amount of time. To overcome this limit, heuristic methodologies involving phylogenetic networks [6, 15], cladistics [16], genetic algorithms [13, 17], and pruning analysis [18] are developed to provide a sub-optimal good solution in a limited time period. This paper follows this stream of research, proposing an easy-to-use methodology based on clustering techniques for the product platform design and assignment to product variants to manage high product variety. While clustering techniques are used extensively in group technology (GT) and cellular manufacturing (CM), a methodology applying commonality analysis to product variants' structure within DPD strategy is still missing [19]. The developed hierarchical clustering algorithm adapts the clustering algorithms using similarity indexes, e.g., CLINK and SLINK [20], to design feasible product platforms. The algorithm considers an innovative similarity index, inspired by Bortolini et al. [21], which requires, as initial input, the product assembly cycles, to evaluate the shared components and assembly constraints and returning promising candidates to be derived from a single shared platform. The proposed index is also used throughout the algorithm to evaluate the similarity between the structure of the platforms and the unclustered variants. According to this background and goal, the developed heuristic clustering algorithm and the similarity index are introduced in Sect. 22.2, while Sect. 22.3 provides an application of the methodology to an industrial case study from the fixtures and windows sector, showcasing its efficiency and industrial relevance. Finally, Sect. 22.4 concludes this work with final evidence and future research opportunities.

22.2 Hierarchical Clustering Algorithm for Platform Design

The algorithm creates clusters of product variants sharing the same base structure that represents the associated product platform. Therefore, each cluster is associated to a single product platform from which derive each product variant in the cluster. The more the products in a cluster share the same assembly cycle, the more components will belong to the platform, needing less personalization operations to get the final product variant.

Following the standard literature and industrial practice, the proposed algorithm lies on the following assumptions [6, 16]:

1. the production mix is known, as well as the bill of materials and technological constraints of each product variant;
2. the production cycle is expressed as a sequence of components to be assembled;
3. customization of product platforms is realized by assembly tasks only, i.e., disassembly of components from platforms is not allowed;
4. a product variant can be built from a product platform if the variant technological cycle shares the platform's technological cycle from the beginning.

The algorithm follows a hierarchical agglomerative clustering approach based on the definition of a new similarity index to measure the shared components in the production cycle of couples of entities, i.e., product variants or platforms. The algorithm 5 steps are reported in the flowchart in Fig. 22.1.

The input for the index is a matrix, i.e., the so-called phase-component association (PCA) matrix, structuring each entity's assembly process in phases and associating to each phase the specific component to add to the previous according to the precedence constraints. An example of a generic group of product entities with known assembly cycles and the correspondent PCA matrix is presented in the following Tables 22.1 and 22.2.

Using the information collected in the PCA matrix, the similarity index for the generic couple of entities ab is calculated as the ratio between the number of phases shared by the entities from the beginning of their assembly and the maximum length of their cycle. The similarity index is mathematically expressed as:

$$\boldsymbol{S_{ab}} = \frac{\sum_{i=1}^{I}\left[\left(\sum_{j=1}^{J} \boldsymbol{x_{ijab}}\right)\cdot \prod_{t=1}^{i-1}\left(\sum_{j=1}^{J} \boldsymbol{x_{i-1,jab}}\right)\right]}{\max\left(\sum_{i=1}^{I} \boldsymbol{y_{ia}};\ \sum_{i=1}^{I} \boldsymbol{y_{ib}}\right)} \tag{22.1}$$

where

a, b	entities, $a, b = 1, \ldots, E$.
i	phase of assembly cycle, $i = 1, \ldots, I$.
j	type of component, $j = 1, \ldots, J$.
q_{ia}, q_{ib}	element of the PCA matrix

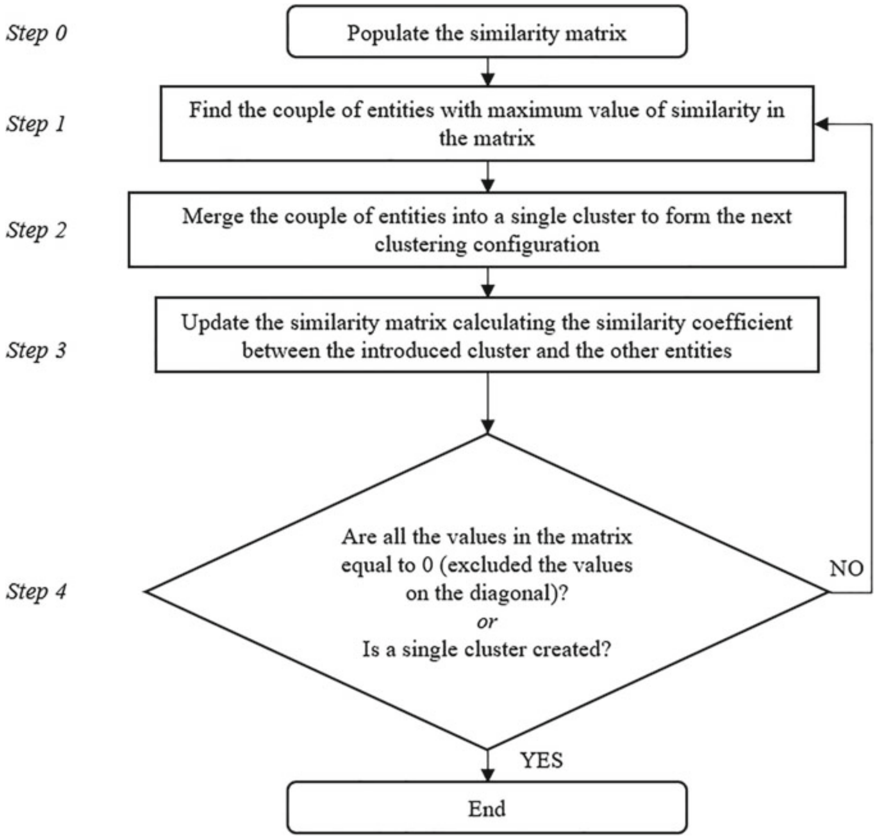

Fig. 22.1 Flowchart of the hierarchical clustering algorithm

Table 22.1 Examples of entities and related assembly cycles

Entity	Assembly cycle
E1	C1–C4–C5–C6–C7–C8
E2	C2–C3–C5–C6–C7
E3	C2–C3–C5–C3–C6–C7–C8

Table 22.2 Correspondent PCA matrix

	Ph1	Ph2	Ph3	Ph4	Ph5	Ph6	Ph7
E1	C1	C4	C5	C6	C7	C8	0
E2	C2	C3	C5	C6	C7	0	0
E3	C2	C3	C5	C3	C6	C7	C8

$$x_{ijab} = \begin{cases} 1 \text{ if } q_{ia} = q_{ib} \\ 0 \text{ otherwise} \end{cases}$$

$$y_{ia} = \begin{cases} 1 \text{ if } q_{ia} \neq 0 \\ 0 \text{ otherwise} \end{cases} \qquad y_{ib} = \begin{cases} 1 \text{ if } q_{ib} \neq 0 \\ 0 \text{ otherwise} \end{cases}$$

The similarity index considers couples of entities evaluating how much their assembly cycles correspond by counting the components required by both in the same position of the cycle. Two entities are considered possible candidates to be derived from a unique product platform if they share the same initial part of their assembly cycles, considering components and their precedencies. Thus, entities assembled from different starting components could not be derived from the same product platform, resulting in a similarity coefficient value equal to zero or close to zero. On the other hand, a high level of similarity is achieved by couple of entities with assembly cycles matching from the beginning and a small number of personalization components at the end of their cycle, facilitating and speeding up the customization process.

Parameter x_{ijab} checks if entities a and b require the assembly of the same component type j in the same generic phase i of their assembly cycles. The parameters y_{ia} and y_{ib} are used to check if a generic phase i requires the assembly of any component for entities a and b, respectively. By adding all the assembly phases, the value of the parameter represents the overall length of the assembly cycle for an entity. The maximum value between y_{ia} and y_{ib} is selected to divide the number of their corresponding components and to weigh the similarity value according to the maximum length of the considered cycles.

As example, according to the information collected in the PCA matrix in Table 22.2, the similarity index value S_{13} for the E1-E3 couple of entities is 0 due to their assembly cycles starting with different component, i.e., C1 for E1 and C2 for E3. Conversely, entity E3 shares with E2 the first three phases of the cycle, i.e., C2-C3-C5, out of the total seven phases of which the assembly cycle of E3 is composed. The corresponding similarity index S_{23} has value $\frac{3}{7} \sim 0.43$.

Starting from the similarity matrix, the hierarchical clustering algorithm starts in *Step 1* identifying the entities, i.e., product variants at the beginning, with the highest value of similarity and aggregating them into a single cluster representing a product platform according to *Step 2*. This platform has an assembly cycle made by the ordered sequence of components that the two variants share from the first phase until they differ and enters the clustering configuration as a new entity. Thus, in *Step 3* the similarity value between this platform and the other product variants is calculated following the definition of the similarity index (1), updating the similarity matrix. From the second iteration of the algorithm, the entities in the matrix represent both product variants and product platforms, associated to the created clusters of variants. Depending on the kind of entities involved in the clustering, the results of an iteration can be the assignment of two variants to a new product platform, the addition of a variant into an already formed platform, or the merge between two platforms into a single one from which derive all the product variants associated to the previous two clusters.

The algorithm iterates until the stopping condition in *Step 4* occurs, resulting in a single cluster representing a unique platform associated to all the product variants or in more clusters impossible to merge due to the different starting components of their assembly cycles. Overall, the results are presented in the form of a dendrogram, and the user selects a solution configuration among the alternative solutions, hence decides where to cut the diagram, according to the real industrial scenario. Cutting the dendrogram close to its initial entities prevents the creation of clusters leading to solutions adopting the DPD strategy for the customization of a small part of similar variants. On the contrary, deciding to cut near the final merging provides platforms associated to a larger number of variants. In this case, to derive the many different variants, a platform will be more generic and made by a few common components.

The proposed heuristic clustering methodology is implemented in a Microsoft Excel environment, using the Visual Basic for Applications (VBA) tool. A real case study in the windows and fixtures sector is used to test the methodology and is reported in the following Sect. 22.3 together with the main results.

22.3 Industrial Case Study

The case company produces fixtures and windows frames through a set of assembly operations and is considering the adoption of a DPD strategy through the design of appropriate product platforms. The considered marketing mix includes 24 product variants ($E = 24$), obtained through the assembly of 14 different components ($J = 14$) according to a product-specific assembly cycle reported in the following Table 22.3.

The assembly cycles are collected in a correspondent PCA matrix, to apply the similarity index (1) and to populate the similarity matrix, input for the clustering algorithm presented in Sect. 22.2. An extract of the similarity matrix is shown in the following Table 22.4a, highlighting 0.9 as the highest similarity value of the first iteration of the clustering algorithm, involving the entities PV1 and PV3 corresponding to product variants. The couple is merged in a single cluster, called CL1-3 representing a product platform associated to PV1 and PV3, and assembled following the shared part of the entity's assembly cycles, i.e., C1-C3-C5-C6-C7-C8-C10-C11-C12. According to the algorithm procedure, the similarity matrix is updated applying the similarity index to calculate the similarity value between the new cluster entity and the other unchanged entities. Table 22.4b reports an extract of the similarity matrix updated after the creation of CL1-3 cluster.

Table 22.3 Assembly cycles for the considered product variants

Product variant	Assembly cycle
PV1	C1-C3-C5-C6-C7-C8-C10-C11-C12-C13
PV2	C1-C3-C4-C6-C7-C8-C10-C11-C12-C13
PV3	C1-C3-C5-C6-C7-C8-C10-C11-C12
PV4	C1-C3-C4-C3-C7-C8-C10-C11-C12
PV5	C1-C3-C5-C6
PV6	C1-C3-C4-C6
PV7	C1-C3-C5-C6-C7-C8
PV8	C1-C3-C4-C6-C7-C8
PV9	C2-C3-C5-C6-C7-C8-C9-C10-C11-C12
PV10	C2-C3-C4-C6-C7-C8-C9-C10-C11-C12
PV11	C2-C3-C5-C6-C7-C8-C10-C11-C12
PV12	C2-C3-C4-C6-C7-C8-C10-C11-C12
PV13	C2-C3-C5-C6
PV14	C2-C3-C4-C6
PV15	C2-C3-C5-C6-C7-C8
PV16	C2-C3-C4-C6-C7-C8
PV17	C1-C3-C4-C5-C7-C8-C10-C11-C12-C13
PV18	C1-C3-C4-C5-C6-C7-C8-C10-C11-C12
PV19	C2-C3-C4-C5-C7-C8-C9-C10-C11-C12
PV20	C2-C3-C4-C5-C6-C7-C8-C10-C11-C12
PV21	C1-C3-C4-C5
PV22	C2-C3-C4-C5
PV23	C1-C3-C4-C5-C6-C7-C8-C10-C11-C12-C13-C14
PV24	C2-C3-C4-C5-C6-C7-C8-C9-C10-C11-C12-C14

Table 22.4 **a** Extract of the similarity matrix in input to the clustering algorithm, **b** extract of the updated similarity matrix after the first iteration of the algorithm

a						b				
	PV1	PV2	PV3	PV4			CL1-3	PV2	PV4	PV5
PV1	1.00				⇨	CL1-3	1.00			
PV2	0.20	1.00				PV2	0.20	1.00		
PV3	**0.90**	0.20	1.00			PV4	0.22	0.30	1.00	
PV4	0.20	0.30	0.22	1.00		PV5	0.44	0.30	0.22	1.00

The clustering of the similarity matrix entities defines at the same time the platforms' structure and their association to the variants to derive. Each clustering configuration corresponds to a particular configuration of the manufacturing activities, indicating the product variants to be managed through a DPD strategy and the personalization components subjected to the customers' choice. As example, the clustering configuration obtained after 14 iterations consists in 6 platforms managing 20 out of 24 variants clustered. The detail of the platform's assembly cycle and their association to the product variants are reported in the following Table 22.5, where the platforms correspondent to the obtained clusters are named from A to F.

The missing product variants, i.e., PV4, PV9, PV17 and PV19, are still unclustered, meaning that they are not associated to any product platforms and have to be managed through a different manufacturing strategy, e.g., MTO or MTS, according to the company considerations and strategy.

As reported in the complete dendrogram provided by the algorithm in Fig. 22.2 above, the algorithm stops in the final configuration consisting of two distinct clusters collecting the totality of the product variants in the company marketing mix. The platform associated to the first clusters is used to derive all the product variants with assembly cycle starting with C1-C3 sequence of components, while the second is associated to all the variants starting with C2-C3. Due to the different starting component, the similarity value between the two clusters is 0, preventing the clusters from the final merge.

The choice of the particular platform configuration to implement, i.e., the level where to cut the dendrogram, is up to the company and depends on the production strategies used to address its marketing positioning. As the algorithm iterates, the number of product variants assembled using the DPD strategy increases while the number of components forming the platforms' structure decreases. This leads to more versatile platforms at the expense of a longer customization time. Cutting the dendrogram close to the initial product variants entities, provides the creation of product platforms associated to product variants sharing a high level of similarity. Thus, the platforms will have assembly cycles more similar to the final product variants cycles, leading to lower customization efforts.

Table 22.5 Clustering configuration after 14 iterations of the algorithm

Product platform	Assembly cycle	Associated product variants (PV)
Platform A	C1-C3	1–3–7–5–6–21
Platform B	C1-C3-C4-C6-C7-C8	2–8
Platform C	C2-C3-C4	10–12–16–14–22
Platform D	C2-C3-C5-C6	11–15–13
Platform E	C1-C3-C4-C5-C6-C7-C8-C10-C11-C12	18–23
Platform F	C2-C3-C4-C5-C6-C7-C8	20–24

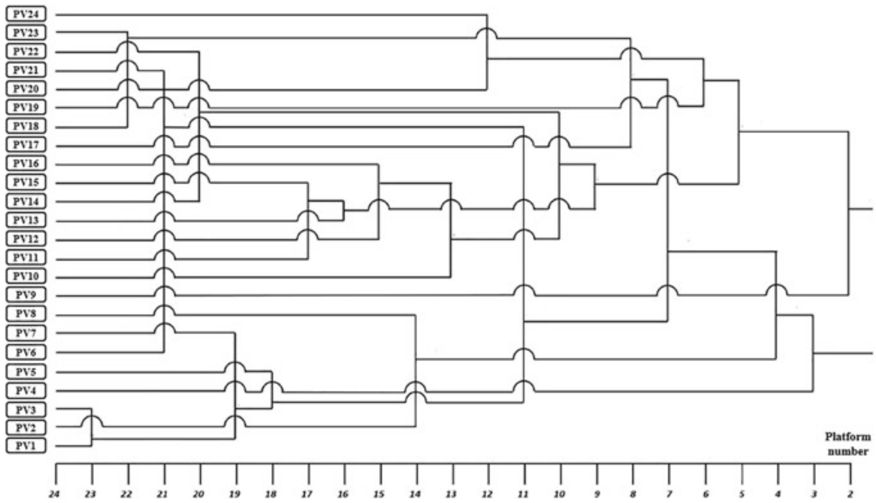

Fig. 22.2 Dendrogram from the hierarchical clustering algorithm application

22.4 Conclusion and Future Research

The changing customer requirements and dynamic market demands are leading to a wide increase of product variety. An effective strategy for the management of product variety is the delayed product differentiation, using product platforms to join the dual needs of high-variety and low customer lead time. This paper contributes to this stream of research proposing and applying hierarchical clustering algorithm for the product platforms design and assignment to product variants. The algorithm considers a similarity index evaluating the possibility to derive product variants from a shared platform by analyzing their production cycles and components precedencies. The agglomerative algorithm merges entities with the strongest cycle similarity creating product platforms to derive the variants through assembly operations. The application of the algorithm to a real case study showcases its use and industrial relevance. Further research has to test the clustering algorithm to other instances providing metrics to support companies in choosing the best cluster configuration.

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Chapter 23
Digital Twins as a Catalyst for Sustainability and Resilience in Manufacturing Systems: A Review from the Supply Chain Perspective

Yujia Luo and Peter Ball

Abstract The rapid advent of digital technologies is reshaping the manufacturing landscape, with digital twins (DTs) surfacing as a transformative innovation. DTs, as virtual counterparts of physical entities or systems, hold substantial potential for optimising and overseeing manufacturing processes. This paper provides an in-depth understanding of manufacturing systems DTs from a supply chain (SC) perspective. A three-dimensional framework is introduced embracing DT integration levels, SC structural hierarchies, and SC processes to examine the evolution of DTs. The paper delves into existing studies concerning these dimensions, identifying a shortfall in structural and process embeddedness of DT implementation within manufacturing systems. Additionally, we delve into major performance objectives and challenges inherent in the DT implementation. This paper provides insights to further the understanding and implementation of DTs in the evolving manufacturing and SC contexts.

23.1 Introduction

The advent of Industry 4.0 marks an era of significant digital transformation within manufacturing processes. This shift has catalysed the emergence of smart factories and intricately connected supply chains (SCs). A technology for driving this transformation is digital twins (DTs), which are virtual replicas of physical objects or systems that facilitate real-time monitoring and optimisation of manufacturing operations [1]. A DT consists of three elements: the physical object or system, the virtual

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replica, and the connecting data that binds these two entities [2]. DTs enable an interactive and dynamic relationship between physical and virtual entities by emphasising real-time bidirectional data flow. DTs provide viable solutions across a multitude of sectors, including manufacturing, aviation, health care, maritime and shipping, urban management, and aerospace and power plant management [3].

The concept of DTs was initially proposed for product life cycle maintenance by Michael Grieves in the early 2000s [4]. Since then, the scope of DTs has expanded, covering different production processes and human and social factors. This evolution in DT application calls for a higher-level reference architecture to align with the objectives of smart manufacturing at the SC level [5]. This architecture would involve multiscale and multi-hierarchy SC processes, encompassing not only product life cycle or production processes but also an extended SC with collaborative business relationships and complex structure. Therefore, the primary objective of this paper is to investigate the multifaceted nature of DTs within multi-level and multiscale manufacturing systems, providing insights into the benefits and complexities of DTs.

DT application is complex due to the dynamic interaction between humans, technology, and processes [6]. The varying nature of SC components, including personnel, equipment, and more, and the nonlinear and multiscale structure of SCs add to this complexity. Additionally, the dynamic and human-related aspects of SC flows make analysis challenging. These factors indicate the necessity for a framework to guide DT design in SC hierarchies. The potential of DT in promoting sustainability lies in its capacity to address a broad range of objectives beyond mere efficiency, providing scalability for system-level improvements.

Considering the above, this paper highlights the importance of SC attributes in the implementation of DTs across multiple scales in manufacturing systems. We provide a review of DT deployment, focusing on factors such as DT integration levels, SC structural hierarchies, and SC processes. Subsequently, we explore the performance objectives in use, highlight challenges and future potential of DTs in manufacturing systems. Notably, we place a particular emphasis on sustainability and resilience in the paper, motivated by the scarcity of literature in this space.

23.2 Dimensions of DTs Implementation in Manufacturing Systems

The DT modelling dimensions cover the characteristics of personnel, equipment, material, process, and environment [7]. To decode the multifaceted applications of DTs [8], we propose a three-dimensional framework for analysing the implementation of DTs by considering the DT level, SC structural hierarchy, and SC processes.

23.2.1 Digital Twin Levels

DTs can be categorised from various viewpoints, such as hierarchical level, life-cycle phase, functional use, data flow, and maturity level [8, 9]. Among these, an approach by Kritzinger et al. [10] differentiates DTs into three categories based on data flow automation between physical and digital objects: (1) digital models, with no automated data exchange, (2) digital shadows, indicating a one-way data flow from physical to digital entities, and (3) digital twins, facilitating bidirectional data flow. While digital models lack real-time interaction with their physical counterparts, digital shadows mirror physical changes without affecting them. Conversely, digital twins enable real-time interaction, reflecting physical changes and implementing suggestions from simulations. In each integration level of DTs, the physical entities consist of physical industry resources such as products, personnel, equipment, material, process, environment, and facilities. This paper uses 'Digital Twin' or 'DT' specifically for the models featuring a two-way data flow between the virtual and physical realms, including materials, products, and possibly other resources.

23.2.2 SC Structural Hierarchy

DTs can facilitate the interaction across various levels in SC systems, from individual components to system integration. Current studies focus more on DT implementation at the machine, product, or shop floor level [11], while the integration of the multiscale nature of SC systems needs to be studied [12]. The broadening scope of DT applications necessitates studying their use across diverse SC levels. As the scale amplifies, it better ensures the consideration of all-encompassing resources, including energy, water, non-product resources, and waste associated with all flows.

Considering the complexity of interconnected SC entities, this study views a SC as a dynamically evolving network of subsystems that foster intra- and inter-system exchanges. Thus, DT-enabled SC systems can be seen as dynamic cyber-physical systems (CPS) that achieve high-level interoperability through DT synchronisation across SC hierarchies [12]. Following [13], this study employs a four-tiered structural hierarchy in SC systems: (1) SC block, a SC process set for a specific business function, is the basic unit in the SC system; (2) SC module that is a collective of blocks fulfilling certain business functions and possibly indicating material or product locations in the SC; (3) SC member, referring to firm-level operators that may comprise one or more modules; (4) SC system, referring to a network of interconnected SC members.

23.2.3 SC Processes

Apart from product lifecycle management, DTs applications have been extended into different SC processes. The supply chain operations reference (SCOR) model advocates for a cross-functional approach and outlines six primary processes: plan, source, make, deliver, return, and enable [14]. These span the entirety of the SC with a primary focus on operational aspects, integrating various departments and functions for holistic SC management. For this study, we lean towards the SCOR model for the investigation of the implementation of DT on SC processes because of its standard representation and hierarchical capability and complement it with the value-adding manufacturing processes. The processes identified from the SCOR model suggest relationship management and the flow coordination of materials, information, and cash [13, 15].

With the understanding of spatial–temporal dynamism of SC structure and processes, DT can be implemented at the SC system level to simulate, analyse, predict, monitor, and optimise the SC behaviours [16]. Across the SC structural hierarchy, SC processes, which include planning, sourcing, making, delivering, returning, and enabling, manifest in each operational unit or 'block' at different scales and scopes. Therefore, our study investigates the multifaceted nature of DT implementation in manufacturing systems, jointly considering DT integration level and SC structure and processes (see Fig. 23.1).

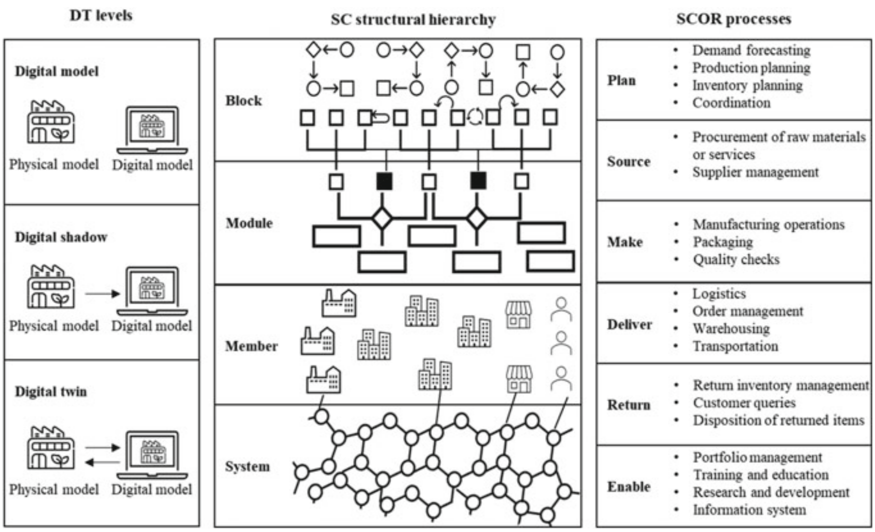

Fig. 23.1 Dimensions of DT implementation in manufacturing systems. (*Source* Authors)

23.3 Implementation of DTs in Manufacturing Systems

The complexity of DTs in manufacturing systems is closely tied to their scalability within the context of smart manufacturing and Industry 4.0 [17]. In this section, we conduct the narrative review guided by the three-dimensional framework (Fig. 23.1), analysing the multifaceted aspects of DTs, including the interplay of integration levels and scalability in SC structures and processes.

DT technology has been employed across various industries, infusing technical functionalities into product design, flow shop design, scheduling, planning, assembly, logistics, and more [18]. Clusters of DTs applications tend to operate in isolation, focusing on the application scenarios (e.g., job-shop scheduling, smart manufacturing, virtualising manufacturing system, product assembly process, and alternative manufacturing), enabling technologies and techniques (e.g., simulation and optimisation), and functionalities (e.g., information management, data analysis, and manufacturing operation management) and expected effects (e.g., sustainability development and SC resilience and risk management) [18, 19]. The emphasis on SC processes and structural complexity is limited, though it is important for the multiscale embeddedness of DT applications.

The literature indicates a scarcity of system-level applications of DTs in the SC context, specifically those that account for the intertwined complexities of processes and structural hierarchies. Studies exploring DTs at the SC level are scarce [19]. The focused areas of DT application are generally based on the individual processes or structural levels of SC hierarchy in Fig. 23.1: ‘blocks’ (e.g., rotating machinery fault diagnosis [20]), ‘modules’ (e.g., logistics and assembly [21]), and ‘members’ (e.g., smart manufacturing [17]). The system-level implementation of DTs in the SC context, particularly those that consider both process and structural complexities across hierarchies, are few. Researchers have proposed the integration of DTs for managing disruption risks and fostering resilience in SCs [22, 23]. Yet, these propositions often focus on individual aspects such as overall ‘system’- or ‘block’-level planning [12] rather than system-wide, holistic solutions that account for the complexities of SC hierarchies. Sustainability and resilience are referred to in DT research [21]; however, few empirical studies that operationalise analysis of this type.

While several researchers have suggested the use of DTs at the SC scale for desirable integration, these concepts remain largely theoretical and need technical support for achieving bidirectional data integration across multiscale SC structures and processes. For instance, Ivanov et al. [22] introduced the concept of data-driven, cyber-physical SCs that harness DTs to assimilate dynamic processes and structures, aiding in risk management without proposing a technical pathway. Serrano-Ruiz, Mula and Poler [23] viewed DTs as a significant enabler within the I4.0 framework for achieving SC resilience and sustainability. Though this framework covers DT integration level, the model fusion across multiple levels and scales is merely emphasised. Zhang et al. [13] emphasised SC business processes for implementing DTs. However, it overlooks the practical execution of DTs across different integration levels and technical pathways for implementation. Aheleroff et al. [6] have proposed a three-dimensional architectural model for implementing DTs. However, this model encompasses the system development lifecycle as one dimension but lacks a clear representation of the involved elements (e.g., ‘blocks’ or ‘modules’ in Fig. 23.1) and their scopes (e.g., different types of processes in Fig. 23.1). In general, these propositions of DT models overlook clear instructions for multiscale integration within SC structures and processes. Moreover, it underemphasises the design of DTs for resilient and sustainable manufacturing systems.

There is a distinct lack of solutions addressing the complex challenges posed by multi-level and multiscale structures and processes for implementing DTs at the SC level. This gap persists, even though some studies have focused on the subsystem scale. For instance, Park, Son and Noh [12] developed a two-level CPS that incorporates logistics planning at both SC and work-centre levels, as depicted in Fig. 23.1’s ‘module’-‘member’ levels. Focusing on the model fusion method for the two-level machine-shop floor system, Zhang, Qi, Tao [11] emphasised the breakdown of machine components and parts at spatial and temporal scales. This study focuses on the assembly line with serial and parallel models and the hierarchical structures in the product bill of materials rather than SC processes. Stavropoulos et al. [24] focused on the automating distinct types of workflows, termed ‘blocks’ in this study, for process monitoring and control. Yet, their exploration failed to delve into the interconnectedness of these workflows spanning across various ‘modules’ or ‘members’ in the SC. Conversely, Wu et al. [25] presented a prototype model focused on system decomposition and subsystem integration, but its focus on the design process neglected wider SC activities. In summary, existing research focuses more on subsystem-level model fusion, overlooking system-level digital twin models within SCs. This underemphasis neglects the need for transitioning from life cycles of individual products to SC systems. It is essential, yet currently needs to be addressed, to align primary objectives towards creating resilient, sustainable manufacturing systems using DT technology.

23.4 Performance Objectives of DT-Driven Manufacturing Systems

Implementing DTs across multiscale SC structures and processes can align with aligning with strategic performance objectives, such as productivity, efficiency, resilience, and sustainability [23]. Efficiency is enhanced through real-time monitoring and optimisation of manufacturing processes, enabling manufacturers to identify and address inefficiencies, improve productivity, and reduce costs [18]. Furthermore, recent studies acknowledged that both sustainable development and SC resilience and risk management are two major objectives [20, 26, 27], especially for agri-food industries [28, 29]. The increased visibility and collaboration facilitated by DTs lead to more agile and responsive SCs, allowing better adaptation to changing market conditions. With end-to-end visibility, DTs enable SC with sustainability attributes by modelling human, policy, and environmental factors [23]. Despite recent studies, sustainability and resilience performance objectives are still narrow and shallow [27, 29], largely due to the insufficient modelling of activities that underpin these performance metrics.

In terms of resilience, DTs contribute by improving asset management and maintenance, reducing the risk of equipment failures and production disruptions [30]. The application of DTs in quality control also helps manufacturers minimise the impact of product defects and recalls, further bolstering SC resilience. Further, through improved visibility and predictive analytics, DTs aid in managing common SC challenges (e.g., bullwhip and ripple effects) [22]. By simulating what-if scenarios in SC processes, DTs enable proactive management of potential disruptions. While DTs can contribute significantly to resilience, existing literature lacks a universal framework that can be applied across various industries, considering the unique resilience challenges of diverse sectors. Moreover, quantifying resilience enhancement to verify the superiority of a DT-enabled manufacturing system remains a tough task. A systematic resilience-focused framework design (integrating inherent resilience attributes and enabling their quantification or measurement) still needs development.

Sustainability, as one of the pillars of smart and intelligent manufacturing [31, 32], is significantly improved through the integration of DTs within the manufacturing SC. By creating virtual replicas of physical assets and systems, DTs facilitate real-time monitoring, predictive maintenance, and dynamic simulations, enabling organisations to identify inefficiencies, reduce waste, and minimise resource consumption [33]. DTs enable sustainable manufacturing systems by promoting collaboration across the SC, streamlining communication, and fostering a more transparent and eco-friendly approach to product and SC system life cycle management [34]. This innovative technology contributes to the reduction of carbon emissions and societal risks. It drives long-term economic benefits [33], positioning businesses to better adapt to evolving sustainability regulations, societal expectations, and market demands [35]. However, there are significant gaps exist in capturing the sustainability enhancement of DT technology in manufacturing systems. Current studies reveal a lack of integration of sustainability into DT models, with the absence of a generic top-down sustainability measurement framework and difficulties in simulating bottom-up sustainability practices. Furthermore, current studies can rarely align sustainability measurement throughout SC system life cycle activities across different scales and scopes.

23.5 Challenges of DT Implementation in Manufacturing Systems

To fulfil on potentials of performance enhancement, several challenges and opportunities of DTs in manufacturing systems must be addressed for their successful implementation.

Firstly, data quality and management. The functionality of DTs relies heavily on the accuracy and comprehensiveness of the data utilised in their creation and maintenance. However, with manufacturing being a process fraught with uncertainties in dimensional accuracy [24], there may be difficulties in data collection, particularly without prior experience or an established real-time data exchange scheme. Ensuring high-quality data involves the utilisation of suitable sensors and data collection methodologies in conjunction with robust data management practices. Though enabling technologies such as sensors and IoT have facilitated the process of data collection, there is still a challenge of real-time data accessibility in industrial practices.

Secondly, design and measurement of resilience attributes. Manufacturing systems are inherently complex and dynamic, characterised by interconnected components and susceptibility to disruptions. Designing resilience attributes for DT models that can effectively capture these complexities remains a case-by-case challenge, even when considering generic factors such as response time, recovery capability, and adaptability [22]. To ensure consistency and comparability, a generic framework is needed to design and measure resilience attributes across industries with the consideration of the multifaceted nature of resilience. However, the development and application of such a framework are often hindered by data availability and accuracy issues. These obstacles impede the establishment of resilience benchmarks, further complicating the verification of model resilience across various scenarios.

Thirdly, sustainability consideration. Considering it in DT models is crucial for achieving sustainable development goals (SDGs). Despite the emergence of the International Organisation for Standardisation (ISO) standards for DTs since 2020 and their contribution to all SDGs, we still lack standard guidelines for integrating sustainability consistently into DT models [5]. This gap limits the comparability and measurement of sustainability performance of DT implementation. The complexity of sustainability dimensions, evolving goals and regulations, and challenges related to data availability further complicate the design and implementation of sustainable DT models. As such, the representation of sustainability issues in DT models and the quantification of improvements attributed to DT technology remain largely conceptual with limited accountability.

Fourthly, organisational changes. DT implementation may necessitate organisational changes, as well as the development of new skills and competencies among the workforce [36]. This requires the implementation of comprehensive change management strategies and targeted training programs to ensure a smooth transition. Importantly, the alterations required are not static but dynamic—as DT implementations evolve, so too must the organisational structures and processes, leading to a cycle of continuous adaptation. This iterative change process can introduce an array of complexities, making it essential to develop an adaptive and learning-oriented organisational culture to effectively navigate this transformative journey.

23.6 Conclusion

In conclusion, the implementation of DTs in manufacturing systems has demonstrated their versatility and applicability across diverse industries, highlighting their potentials across different scales and scopes. This study has introduced a three-axis framework to facilitate the interpretation of the integrated standards for DT implementation in manufacturing systems.

The framework has guided the review of existing literature, revealing a gap in the integration of DT at the system level, both structurally and process-wise. While earlier studies mainly focused on individual components (e.g., machines), recent strides have introduced DT frameworks at the SC level and explored protocols for model fusion across diverse structural hierarchies. This shift signifies a more comprehensive approach to DT implementation in manufacturing systems, acknowledging the complexities inherent in both the SC structure and processes involved.

Efficiency, resilience, and sustainability are recognised as key performance objectives of DTs in manufacturing systems. The advantages of DTs in enhancing resilience and sustainability stem from streamlined processes, visibility, real-time monitoring, waste reduction, and integration of environmental policies and societal concerns. However, the assessment framework for resilience and sustainability in DT-enabled manufacturing systems is still in its infancy and requires further exploration. Specifically, the complex facets of resilience, sustainability, and DT technology amplify the difficulty in creating a standard framework. Further, data availability and precision pose obstacles in representing DT-enabled enhancements. Addressing these challenges requires adaptable modelling approaches and robust data management strategies.

DTs have emerged as a promising innovation in the manufacturing domain with desirable performance effects. However, their successful implementation necessitates addressing challenges related to data quality and management, security and privacy, interoperability and standardisation, resilience and sustainability consideration, and organisational changes.

In conclusion, DTs hold great promise in transforming the manufacturing landscape and driving innovation. By embracing DT technology and addressing associated challenges, manufacturers can enhance their competitiveness and contribute to the development of more resilient and sustainable manufacturing systems for SDGs [37]. This integration of DT with sustainable manufacturing principles promotes responsible production and consumption, which is crucial for addressing global challenges. Thus, DT, as a core concept of smart manufacturing, plays a pivotal role in shaping a sustainable future in manufacturing.

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Chapter 24
Transforming E-Waste into Value: A Circular Economy Approach to PCB Recycling

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Abstract This study delves into the pressing global issue of electronic waste (e-waste), with a specific emphasis on printed circuit boards (PCBs). PCBs, being a crucial component of electronic devices, contribute significantly to e-waste due to their intricate composition of hazardous substances and valuable metals such as gold, silver, and copper. The research explores the concept of the circular economy—an economic system aimed at eliminating waste through the continual use of resources—and its potential application in recycling PCBs. This involves a detailed investigation of the challenges and opportunities associated with various extraction methods and waste management strategies. The study also presents a case study on The Royal Mint's innovative approach to gold extraction from PCBs. This practical example offers valuable insights into the application of circular economy principles in the context of PCB recycling, demonstrating how these principles can lead to improved resource efficiency, waste reduction, and economic benefits. The findings of this research underscore the need for further development and implementation of sustainable practices in e-waste management to mitigate environmental impact and capitalise on the economic potential of valuable materials in e-waste.

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24.1 Introduction

Swift technological advancement and escalating consumer demand for electronic devices have resulted in a significant surge in e-waste generation [1]. This problem is further magnified by the absence of efficient waste management strategies, thereby leading to environmental and health hazards [2].

The global electronic waste problem has become a significant concern, driven by the rapid growth in electronic devices and their limited lifespans. The rise in modern lifestyles, technological advancements, and global economic progress has led to a significant increase in e-waste, which is causing serious environmental and health problems. Around two billion metric tonnes of waste are generated worldwide each year, with e-waste accounting for 53.6 million tonnes. The amount of global e-waste has been rapidly increasing, reaching 53.6 million tonnes in 2019, a 21% increase since 2015. Unfortunately, most of this e-waste (about 83%) is not properly documented and is likely burned or dumped illegally, posing a threat to both people and the environment. Only 17% of the e-waste produced in 2019 was collected and recycled correctly. In terms of continents, Asia produces the highest amount of e-waste (46.4% globally) in 2019, followed by America, Europe, Africa, and Oceania. However, when we consider the amount of e-waste per person, Asia produces less waste per person compared to Europe, Oceania, and the Americas due to its large population. Africa has the lowest e-waste generation per person [3]. According to the Global-E-waste-Monitor 2020 report by the United Nations University (UNU), United Nations Institute for Training and Research (UNITAR), and International Solid Waste Association (ISWA), 53.6 million metric tonnes (Mt) of e-waste were generated globally in 2019, marking an increase of 9.2 Mt from the previous five years. Disconcertingly, only 17.4% of e-waste was officially collected and recycled [4]. E-waste is highly heterogeneous in nature, composed of various systems housing a diverse range of metals, polymers, and ceramics, thereby being considered as potential secondary resources [4].

PCBs are a key component of electronic waste owing to their universal usage in electronic devices. PCBs have a complex composition, incorporating hazardous substances along with valuable metals such as gold, silver, and copper. The presence of these precious metals has sparked interest in the development of new recycling technologies [5]. However, traditional methods for gold extraction face several challenges, including inefficiency, resource exhaustion, and environmental pollution. Besides, complex and heterogeneous structures of PCBs, including different metals, polymers, and ceramics, pose technical and environmental challenges [6].

E-waste management and recycling are attracting considerable attention due to the presence of precious, critical, or strategic metals combined with the associated environmental burden of metal recovery from natural mines [4]. The direct disposal of e-waste into the environment triggers environmental and human health risks. Improper e-waste recycling practices in developing countries have resulted in the generation of toxic gases such as dioxin and furan (polychlorinated dibenzo-p-dioxins and dibenzofurans), posing environmental and human health risks [7]. The release of acids,

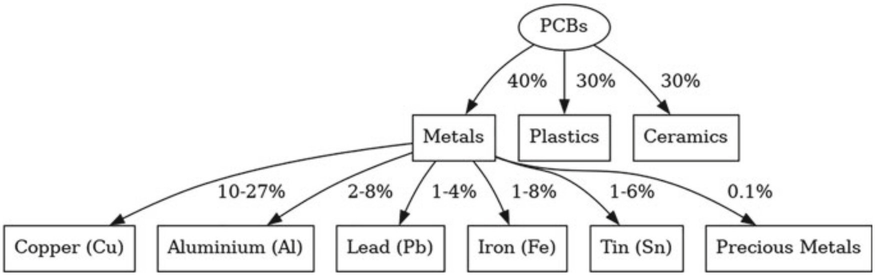

Fig. 24.1 Composition of PCBs. The diagram illustrates the average composition of PCBs, including the breakdown of the metal fraction. Data sourced from [9]

heavy metals, lethal chemicals, and compounds from e-waste can have adverse effects (direct or indirect) on the entire biosphere [7]. Sustainable solutions and the principles of a circular economy present a promising approach for managing PCB waste and extracting gold. The circular economy advocates for the reutilisation of beneficial materials to prevent pollution and manage secondary materials. This strategy can facilitate the achievement of social, economic, and environmental benefits [8].

PCBs represent some of the most valuable elements within waste electrical and electronic equipment (WEEE), making their recovery both economically and strategically advantageous. However, the composition of PCBs can considerably vary based on their place of origin, year of manufacture, and the appliance they were employed in. As illustrated in Fig. 24.1, the composition of PCBs consists of 40% metals, 30% polymers, and 30% ceramics, with the metal fraction further broken down into various elements [9].

The primary aim of this paper is to analyse the prospective application of circular economy practices in recycling PCBs. The circular economy is a model that promotes the efficient use of resources, minimises waste, and encourages the recycling or reuse of materials. In the context of PCBs, this involves investigating strategies for the recovery and reuse of valuable metals such as gold, silver, and copper, as well as the safe disposal or repurposing of hazardous substances.

The paper endeavours to offer a comprehensive overview of the current state of PCB recycling, including the challenges and opportunities tied to various extraction methods and waste management strategies. It further seeks to underscore the economic, environmental, and social implications of these practices, specifically focusing on the role of gold extraction in fostering economic sustainability and lessening environmental impact. In addition to scrutinising existing literature and research on the subject, the paper will incorporate a case study on The Royal Mint's usage of PCBs for gold extraction. This case study will provide a practical illustration of how circular economy principles can be applied in the context of PCB recycling, offering valuable insights into the benefits, challenges, and potential implications of this approach.

24.2 Methodology

Our methodology began with a comprehensive literature review to understand the composition of PCBs and the challenges associated with their disposal. We examined previous studies and reports to gain insights into the hazardous substances and valuable metals contained in PCBs. We then conducted an in-depth analysis of various gold extraction techniques from PCBs. Each method was evaluated based on its efficiency, environmental impact, and feasibility for large-scale implementation. Subsequently, we explored the concept of a circular economy and its relevance to PCB waste management. We studied how circular economy practices such as recycling, refurbishing, remanufacturing, and material recovery could be applied to mitigate e-waste and foster a circular economy. The implementation of the 3Rs principle (reduce, reuse, recycle) in e-waste management was also discussed.

Finally, our methodology incorporated a case study analysis of The Royal Mint's initiative to recover precious metals from electronic waste. We analysed their partnership with the Canadian clean tech start-up Excir and the patented technology they use to recover over 99% of gold from discarded electronic devices. This case study provided a practical example of applying circular economy principles in the context of PCB recycling. This systematic approach allowed us to gain a comprehensive understanding of the challenges and opportunities associated with PCB recycling and to explore innovative solutions for e-waste management.

24.3 Background

24.3.1 PCBs and Gold Extraction

PCBs are integral to electronic devices, significantly influencing their functionality. Comprising multiple layers of glass fibre and copper, these are safeguarded against oxidation by a solder mask. This mask, however, impedes the exposure of metals to lixiviants in waste PCB recycling processes [10].

The extraction of precious metals from PCBs involves a key step known as PCB milling. This process commences with the manual breakdown of PCBs, which are then shredded and undergo hammer milling. The milling time and feed mass ranges are controlled to optimise the release of the desired metals. Post-extraction, the remaining PCB material is handled based on its behaviour during milling and the distribution and liberation of each component. This understanding is crucial for optimising subsequent processing stages [6].

The management of PCB waste is a complex issue due to the diverse and intricate materials involved. Current strategies primarily focus on the recovery of valuable metals, with only a minor portion of the materials being recycled. However, advancements in technology and methodologies are paving the way for improved recycling processes and recovery of valuable metals. From an environmental perspective, these advancements can contribute to reducing the volume of waste in landfills. Economically, the recovery of precious metals can generate revenue. Socially, sustainable PCB waste management practices can stimulate the creation of green jobs and promote corporate social responsibility [11].

Recycling processes for PCBs can be broadly segregated into thermal and non-thermal procedures. Non-thermal processes, encompassing methods like electro/hydrometallurgical processes, are accompanied by specific operational challenges and environmental concerns. Health risks arise for milling operators due to potential inhalation of fibreglass particles and heavy metals. The milling process also results in a strong, unpleasant odour generated by phenolic resin. These methods necessitate significant investment in wastewater treatment apparatus. Environmental impacts include high water usage, wastewater generation with acidic residues, noise pollution from grinding machinery, and the generation of solid waste. Conversely, thermal processes or pyrometallurgical recovery present different challenges and environmental issues. Non-metallic materials cannot be recovered through these procedures, and there is a considerable upfront cost in equipment and installation, including air pollution control systems. Moreover, the economic efficiency of these processes for low-grade waste is yet to be substantiated. The major environmental impacts of thermal processes include the production of gaseous pollutants, notably dioxins, and lead fumes. Notably, in the metal recovery system, multiple processes might be utilised in tandem, such as milling, which is commonplace in most systems for metal recovery from discarded PCBs [12].

Gold extraction from PCBs presents an economic and environmental concern of considerable magnitude. Conventional gold extraction methods encompass chemical leaching and smelting. Chemical leaching utilises chemicals to dissolve the gold, facilitating its separation from the remaining material. In contrast, smelting involves subjecting the material to high temperatures to extract the gold. Nevertheless, these traditional methods present several restrictions and challenges. For instance, they often yield low recovery rates, resulting in substantial amounts of unextracted gold. Their environmental impact is also high due to the employment of hazardous chemicals and the emission of harmful by-products. Additionally, these methods are energy-demanding, leading to considerable energy consumption [13]. In response to these challenges, alternative gold extraction techniques have been developed. These comprise hydrometallurgical processes, bioleaching, and electrochemical methods. Hydrometallurgical processes entail the use of aqueous solutions for metal extraction, while bioleaching employs bacteria to dissolve metals [10]. This environmentally friendly method has the potential for high recovery rates. Nonetheless, bioleaching is primarily in the experimental phase and has not seen widespread adoption in the industry [14].

24.3.2 The Circular Economy and PCBs

The concept of a circular economy (CE) is a sustainable economic development model championing the reuse of valuable materials to limit pollution and manage secondary resources. This method is especially relevant to managing PCB waste because of the valuable materials they contain and the environmental hazards caused by their improper disposal [3]. Within the context of PCBs, circular economy practices encompass recycling, refurbishing, remanufacturing, and material recovery. The recycling and retrieval of materials from PCBs are integral for mitigating e-waste and fostering a circular economy. The 3Rs principle (reduce, reuse, recycle) is a commonly adopted tactic in e-waste management, incorporating reducing e-waste, reusing potential e-products or e-waste, and recycling irreparable e-products [15].

Refurbishing and remanufacturing are also essential aspects of the circular economy's strategy for managing PCBs. For instance, Fairphone, a smartphone manufacturer, has gained recognition for its sustainable design and resource efficiency. This includes assessing the end-of-life phase of their products and strategising how to recover the majority of materials in their phones post their functional lifespan [16].

Adopting circular economy principles in PCB recycling brings several environmental, economic, and social benefits. The circular economy approach encourages the reuse of valuable materials to reduce pollution and manage secondary materials recovered in e-waste streams [17]. This method can facilitate enhanced resource utilisation, pollution prevention, and the realisation of sustainable development goals (SDGs) such as SDG 11 (sustainable cities and communities) and SDG 12 (responsible consumption and production) [18].

Despite these benefits, implementing circular economy practices in the PCB industry comes with some challenges. Technological constraints, regulatory frameworks, and stakeholder engagement are among the considerable barriers. For instance, many countries with growing economies lack sophisticated technologies to recover materials from PCBs. Additionally, e-waste management faces barriers due to inadequate financial backing, deficient infrastructure, scarce technical skills, and limited community engagement [17].

Regulatory frameworks also pose challenges, as effective e-waste management calls for policy approaches underpinned by sustainability principles and buttressed by science, technology, and innovation. These comprise restrictions on e-waste export or import, regulations on recycling certain e-waste categories, and the implementation of extended producer responsibility [17]. Stakeholder engagement emerges as another pivotal aspect. For instance, implementing extended producer responsibility and the 3Rs strategy in electronics manufacturing regulations globally can promote the production of products intended for reuse rather than obsolescence [17].

24.3.3 Eco-Friendly Solutions for PCB Waste

Eco-friendly solutions for managing PCB waste include recycling, reuse, and recovering materials. These strategies aim to lessen the environmental impact of PCB waste and increase recycling rates. Innovative technologies and methodologies are under investigation to enhance PCB recycling and the recovery of valuable metals. For instance, a recent study suggested a method to recycle copper nanoparticles from PCB waste etchants via a microemulsion process. This approach not only recovers valuable materials but also mitigates the environmental footprint of PCB waste [19]. Another work [20] also indicated a strong preference for recycling, particularly due to the economic aspects of e-waste processing, which are acknowledged as another important criterion. Waste recycling, especially e-waste recycling, can lead to advantageous economic impacts, such as the recovery of valuable and precious materials, conservation of natural resources, energy saving, job creation, and landfill saving. The monetary value of e-waste raw materials is estimated to be $57.0 billion. However, only $10.0 billion worth of e-waste is recycled and recovered sustainably, counteracting 15.0 million metric tons of carbon dioxide equivalents [3].

However, the informal recycling of metals from waste PCBs, particularly in developing countries, has resulted in severe environmental pollution and human health risks. Implementing the 'Twelve Principles of Green Chemistry' is the most effective strategy to address these issues [21]. The authors proposed a green process for metal recycling that co-processes waste PCBs and spent tin stripping solution at room temperature. The green process has substantial advantages over traditional recovery methods of heating waste PCBs, in terms of both material and energy efficiency [21].

Putting these solutions into action is not without challenges. For instance, the wide range and complexity of WEEE, which includes PCBs, poses significant problems for waste management plans. One of the main difficulties noted by many researchers is separating components and materials, due to their diversity, so they can work as needed in the devices. To separate the electronic components and reuse the materials, they need to be detached from the solder, which is a complex process, and it often ruins the components because of the heat used [11].

Our future heavily relies on how we manage our waste. Proper waste management can reduce our global impact and is a crucial part of sustainable development. Ignoring waste issues could lead to serious health, environmental, and financial problems. If we do not handle, monitor, and regulate electronic waste properly, illegal activities could increase, harming our efforts to protect health and the environment and create decent jobs. It is estimated that each year, the European Union exports between 0.5 and 1.3 million tons of used and waste electronic and electrical equipment. This is between 16 and 38% of the collected e-waste. Illegal waste recycling is a problem for the legal waste business. When new European rules on electrical and electronic equipment were introduced, the UK's recycling industry expected about 1.5 million tons of e-waste for yearly processing. But when these amounts did not appear, UK officials started an investigation and found that up to 1 million tons, or two-thirds of the UK's e-waste, is not sent to the right recycling facilities but instead is sent overseas. The estimated result is around a USD 7.5 million profit loss to local treatment of waste electronic and electrical equipment [22].

24.4 Royal Mint Case Study

The Royal Mint, renowned for its expertise in coin minting and precious metal production, has embarked on a pioneering venture to recover precious metals from electronic waste. This initiative, in partnership with the Canadian clean tech start-up Excir, utilises a patented technology capable of recovering over 99% of gold from discarded electronic devices, such as laptops and mobile phones. This innovative approach not only offers a solution to the escalating e-waste problem but also aligns with the principles of a circular economy by turning waste into a valuable resource [23].

By specifically targeting components such as PCBs, The Royal Mint has devised a process to extract valuable precious metals, including gold. These metals, once deemed waste, are now being reclaimed and repurposed, contributing to a more sustainable and circular economy. The e-waste recycling process at The Royal Mint involves several stages, each presenting its unique challenges. Figure 24.2 provides a simplified representation of the process, which begins with the collection of electronic waste and concludes with responsible waste management, ensuring minimal environmental impact. The Mint is continually exploring ways to optimise its operations, maximise resource recovery, and minimise environmental impact.

Cardiff University, as part of the TransFIRe program [24], is working with The Royal Mint to make this process even more sustainable and minimise the current waste streams or find more sustainable solution for the current by-products streams. By focusing on these areas of improvement and collaborating with partner organisations, researchers, and technology providers, The Royal Mint can continue to lead the way in sustainable e-waste recycling practices. This collaboration underscores The Royal Mint's commitment to sustainable e-waste management and its role in promoting a circular economy.

The Royal Mint's endeavours to recover precious metals from electronic waste represent a significant stride towards reducing reliance on primary mining and promoting responsible use of finite resources. Embracing the principles of the circular economy, they demonstrate the potential to transform electronic waste into valuable secondary resources. This innovative approach not only provides environmental benefits but also presents economic opportunities. The recovered precious metals can

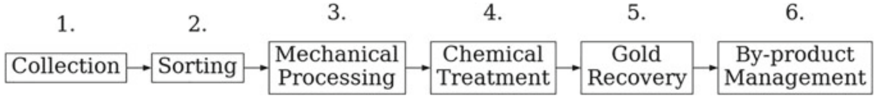

Fig. 24.2 Simplified representation of The Royal Mint's process for gold recovery from PCBs

be reintroduced into the supply chain, supporting sustainable manufacturing practices and reducing the demand for new materials. Through extensive research and development, The Royal Mint has refined their methods for efficiently and effectively recovering precious metals from electronic waste. This involves employing advanced technologies, such as selective leaching and precipitation, to separate and purify the metals from the PCBs. By doing so, they achieve high material yield percentages and minimise environmental impact.

The precious metals recovered from this process are later used in the production of a new jewellery line, 886, launched by 28-piece gender-neutral sustainable collection of which 70% currently being produced in Llantrisant, South Wales by The Royal Mint. The jewellery is made sustainably, using e-waste precious metals. Solid gold and silver pieces are 'struck' like coins rather than being 'cast' a process superior to casting as it makes the product 30% stronger with more lustre [25]. As the global demand for electronic devices continues to surge, The Royal Mint's work serves as a valuable case study, showcasing the potential for collaboration between the metal industry and the recycling sector. Their efforts inspire further exploration and partnerships to develop scalable and sustainable solutions for electronic waste management, ultimately contributing to a more circular and resource-efficient future.

24.5 Conclusion

The study concludes that the management of electronic waste, particularly PCBs, presents significant challenges but also unique opportunities. The extraction of valuable metals from PCBs, whilst currently facing constraints and challenges, holds immense potential for economic and environmental benefits. Alternative methods of gold extraction, although promising, require further research and development to enhance their efficiency and feasibility for large-scale implementation. The concept of a circular economy, which champions the reuse of valuable materials to curb pollution and manage secondary resources, bears particular relevance to PCB waste management. However, the implementation of these practices is not without its challenges, including technological limitations, regulatory frameworks, and stakeholder engagement.

The case study of The Royal Mint serves as a practical example of how circular economy principles can be applied in the context of PCB recycling. Their innovative approach to gold extraction from PCBs showcases the potential for collaboration between different sectors to develop scalable and sustainable solutions for e-waste management.

As the global demand for electronic devices continues to surge, the need for effective and sustainable e-waste management strategies becomes increasingly critical. The Royal Mint's work inspires further exploration and partnerships to develop scalable and sustainable solutions for electronic waste management, ultimately contributing to a more circular and resource-efficient future. In conclusion, the study underscores the importance of continued research, innovation, and cross-sector collaboration in advancing sustainable practices in e-waste management and contributing to a more sustainable and resource-efficient future.

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