Smart Innovation, Systems and Technologies 262

Steffen G. Scholz
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Sustainable Design and Manufacturing

Proceedings of the 8th International Conference on Sustainable Design and Manufacturing (KES-SDM 2021)

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Preface

Given the rate of expansion of recent advanced design and manufacturing technologies, there exists a real need for parallel sustainability development for these technologies. Especially, these hi-tech technologies are considered to be key enablers for the modern industry with the ability to revolutionize manufacturing with new processes, materials and applications. Their growth is driven by and plays a significant part in driving the enthusiastic demand for a more sustainable and competitive economy. However, enhancing the business atmosphere in the three dimensions of sustainability (social, environmental and economic) will enable to unleash the full potential of these technologies. In this context, the SDM-21 provided excellent opportunities for the presentation of interesting new research results and discussion about the thematic topic “sustainable design and manufacturing”, leading to knowledge exchange and the generation of new ideas.

KES International and I would like to welcome you to this volume, which forms the proceedings of the Eighth KES International Conference on Sustainable Design and Manufacturing (SDM-21), organized by KES International as an online conference between the 15th and 17th of September 2021. The conference was originally planned to take place in Split, Croatia. However, due to the ongoing Covid-19 pandemic, and with the idea of keeping our attendees safe, the decision to conduct a virtual conference was taken. Hopefully next year, we will see each other once again for SDM-22.

SDM conferences have always attracted excellent contributions, for which we are grateful; we are also pleased to see so many new contributors to SDM-21 even though it was only a virtual conference. We welcome you all and hope that you can be part of the growing body of academics pursuing sustainability research and would like to contribute to the organization of future conferences. We hope that the format still allowed the building of new relationships that further promote future academic and professional collaborations.

This virtual conference nevertheless proved an excellent stage for the presentation of state-of-the-art research and for conducting deep scientific discussions about the latest progresses being made regarding the theory and applications of sustainability in design and manufacturing, contributing to greater knowledge sharing and ideation of new innovative solutions for our problems of today. The topics included both the aspect of sustainability in design and the development of sustainable products and processes through advanced manufacturing. The fields of applications included progress being made in all steps of a product lifecycle, including right from product ideation, design, the complete process chain, as well as modelling, simulations and end-of-life assessment; therefore, a holistic approach to sustainable production is being made.

This conference builds on the successes of the previous seven conferences held so far led 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, held in Budapest, Hungary (2019); and Karlsruhe Institute of Technology KIT, Germany, held on the new KES Virtual Conference Centre platform (2020).

Once again, the conference was comprised of a general tracks chaired by leading experts in the fields of sustainable design, innovation and services; sustainable manufacturing processes and technology; sustainable manufacturing systems and enterprises; and decision support for sustainability. The topic of sustainability is one of the most dynamic fields of research, and that is reflected by the diverse nature of technical- and management-related papers presented at SDM-21. The trend shows that combining both these aspects shows great promise for the future development of sustainable design and manufacturing.

We also thank our Programme Committee members, chairs of general tracks and our special invited sessions, authors and reviewers for their unwavering commitment to ensure the quality of the work submitted, revised and accepted to SDM-21 was of the high standard required by Springer Nature proceedings.

Steffen G. Scholz
Robert J. Howlett
Rossi Setchi
SDM-21 Conference Chairs

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Sustainability Driven Product-Service Systems Development: A Case Study in a Capital Goods Manufacturing Company

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Abstract. This paper aims to present early considerations in the process of Product-Service System (PSS) development driven by sustainability in a capital goods manufacturing company. Based on the elicitation of drivers and barriers for such companies to introduce PSS, the empirical study described in the paper reports on the experiences from representative professionals within the case company gained through a series of interviews. The conducted investigation reveals that whilst displaying some basic similarities, the focus of PSS development in capital goods manufacturing companies is characteristically different than in other manufacturers. Key differences include that capital goods manufacturers ought to: see co-creation of the offering with the customer as being of crucial importance (to ensure efficiency and effectiveness); place a stronger focus on the use phase of their products and related services (to extend the useful life of the product); and be granted ready access to customers' products and their use data (in order to pro-vide through-life services). Differences have also been observed in the way that different parts of the manufacturing organization perceive drivers and barriers for the introduction of PSS.

Keywords: Product-Service Systems (PSS) · Capital goods manufacturer · Drivers · Barriers

1 Introduction

Driven by the earning opportunities on one side and environmental responsibility on the other, manufacturing firms are looking into alternative business models capable of capitalizing on both [1]. Business models within the Circular Economy (CE) paradigm have the potential to address the needs of manufacturing firms by a different, circular means of value creation [2]. The goal of such a paradigm is to reach mutually reinforcing business and sustainability drivers [3], thus decoupling value and wealth creation from resource consumption. Product-Service System (PSS), although not necessarily sustainable or circular [4], is one of the most promising ways of realizing the CE goal of decoupling economic success from material consumption, by means of proactively building in new forms of value creation that either more effectively utilize the material goods, or supplement them, through activity- and knowledge-based offerings [5].

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Despite the wealth of literature addressing PSS design [6], there is a lack of knowledge about the exact offering development process that a manufacturing company is to adopt and conduct to systematically and repeatedly introduce PSS offerings. The knowledge gap widens further when focusing on a specific kind of manufacturing companies that produce capital goods [7], where PSS encounters distinct barriers related to a large number of installed products with long life cycles.

Manufacturing companies currently secure a significant part of their revenue through point-of-sales of physical products [7]. There is, however, an increasing trend among capital goods manufacturers to acquire more significant shares of revenue from through-life services, capitalizing on the already installed base of products, both from the business and sustainability perspectives [8]. A service-based model could extend product life and reduce the manufacture of new products, hence decreasing the environmental impact [5]. Lack of knowledge, resources and customers insights are just some of the many challenges to overcome in the process of PSS development. Focusing on a capital goods manufacturing company, this paper charts and compares literature and empirical findings, regarding the drivers and barriers for the introduction of PSS, with an aim to support the process of PSS development.

2 Methodology

Research Questions. This paper aims to showcase real-world drivers and barriers in the early development process of PSS within a capital goods manufacturing company. Hence, the following research questions were formulated:

1. What are the internally perceived drivers and barriers for the introduction of PSS and how do they compare to literature findings?
2. How do the different parts of the capital goods manufacturing organization perceive drivers and barriers for the introduction of PSS?

Data Collection and Analysis. The principal data for this paper was retrieved through the empirical study based on semi-structured exploratory interviews in a single case company. The single case study is considered an appropriate approach as it allows for a thorough research enquiry and it provides a new lens on important exceptions that question the *status quo* [9]. The empirical study is supported by a previously conducted literature review by the authors on drivers and barriers in capital goods manufacturing companies to introduce PSS [10].

The interviews followed a conventional sequence according to Robson and McCartan [11]. Before the interviews, all interviewees were introduced to the field of PSS through a video presentation, prepared by the author. The purpose of the "video pre-read" was to introduce the interviewees to the terminology, provide sufficient time to reflect on the topic and relate the topic of PSS to their own experiences within the company. The interviews were designed around two main questions:

1. What motives does the company have to introduce PSS?
2. What challenges can you think of to introduce PSS?

In total, 18 interviewees covering diverse functions (R&D, sales, field engineering, etc.) and seniority levels (CxO, team lead, manager) were selected to participate in the interviews. Any function that has a relation to the service provision was aimed to be included to paint a comprehensive picture of perceptions throughout the company. The interviews were recorded and transcribed, resulting in more than 150 pages of interview data. Data were analyzed through inductive research analysis and the analytical reflection of the data was done by the emergent identification of patterns [12].

Case Company. The empirical context for this research is a capital goods manufacturing company. The company is in the business of producing machinery and equipment for the food and beverage industry. At the time of writing, the company is in the early stages of the development and introduction of PSS for its business. The company has the ambition to adopt PSS as a means of increasing its competitiveness on the market that could potentially also contribute to its sustainability strategy.

3 Empirical Insights

Drivers and barriers as elicited from the interviewees were classified into three categories: (i) strategic, (ii), tactical and (iii) operational, corresponding to different levels of the organization. The strategic category encompasses long-term objectives, relations, and value creation. The tactical drivers and barriers are oriented towards more specific goals and performance indicators, while the operational level includes individual actions. These categories also correspond to different seniority levels of the interviewees, where executives are classified as a strategic position, mid-managers as tactical positions, and operational position implies functions in the manufacturing facility or similar. Responses were classified axiomatically in the three categories, with respect to the temporal and executional horizon that the respondents felt each driver and barrier to be.

Through the interviews and literature review, a total of 37 drivers and 45 barriers were elicited for the introduction of PSS. Nineteen drivers were classified as strategic, 13 as tactical and 5 as operational. Complementing the findings from the literature, 8 new drivers and 5 new barriers were revealed. Some of these were not present in the literature, while some had a noticeably altered perspective than in the literature, seen from the perspective of the capital goods manufacturing company. This discrepancy in the number of identified drivers and barriers in the literature highlights the relevance of combining literature studies with empirical studies, especially when applying to new and more specific contexts, such as the capital goods sector.

Interesting trends can be observed in Fig. 1, showing the relation of drivers and barriers in each of the three categories. It is evident that barriers tend to be more tactical and operational than strategic, on the other hand, drivers tend to be more strategic. This incongruity is of special importance in the early phase of PSS development, or even in the company's strategy development. It is relatively straightforward to see the benefits that PSS might bring on a strategic level, and not so many barriers are perceived to adopt it as a strategic goal, however, as the high-level goals become more operational, many barriers appear that deflate the expectations. Therefore, an in-depth study like this might

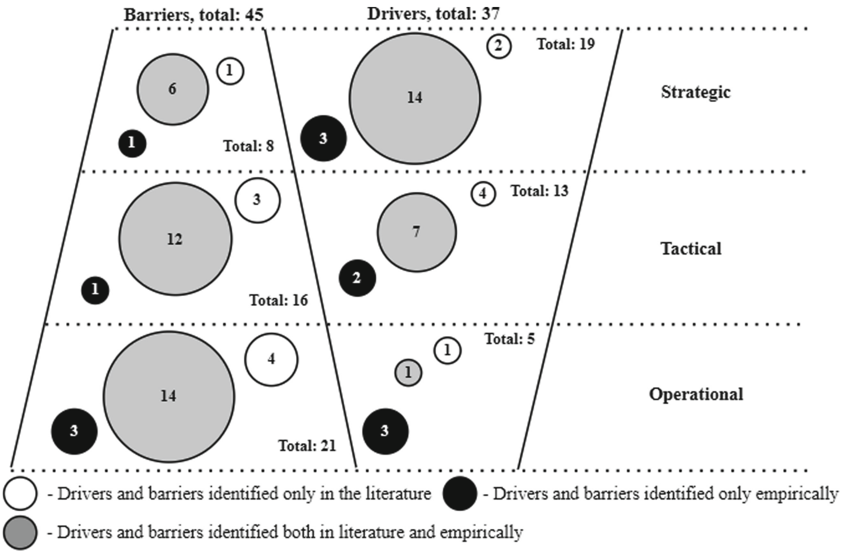

Fig. 1. Classification of drivers and barriers for PSS development elicited empirically and through literature review in three different categories: strategic, tactical, and operational.

bridge the classic mismatch between strategic and operational levels and make the PSS development process and expectations more transparent.

The following sections elaborate on unveiled drivers and barriers for PSS development in a capital goods manufacturing company. This overview is focused on the drivers and barriers that were brought forward most often by the interviewees.

Drivers. *Strategic.* The overarching strategic driver for the case company to introduce PSS is sustainability. This driver is organized according to the triple bottom line, tackling environmental, social and economic dimensions, respectively. These dimensions more specifically mean that PSS is driven by the desire for stronger and long-lasting partnerships, reduced environmental impact and increased and stabilized revenue over time, which are all already recognized drivers [8, 13]. One of the interviewees said: "*CO_2 emission reduction is our biggest strategic target.*", while another said: "*We need to be less dependent on individual transactions and build recurring income streams.*"

Many interviewees pointed out the importance of customer involvement in the development process of PSS, but also the interaction with the customers and products throughout the products' lifetime. A comment from one of the senior managers was: "*Introduction of services will bring product development closer to customers",* while another said: *"…if we get deep insight into the performance of our products, we could get insight into the behaviour of our customers and that is a key differentiator from most of the competition."*. Some of the authors mention customer involvement and knowledge sharing as drivers [6], however, most of them focus on the pre-use involvement, while the use phase of capital goods seems to be of greater impact in the B2B context, both in financial and environmental terms [14]. Strategic differentiation among the competition is one of the most mentioned drivers for the introduction of PSS [15].

Drivers recognized by the interviewees are the adoption of the culture around value in use and the total cost of ownership (TCO) for the installed base of products. One of the senior managers stressed that: "*there is an abundance of opportunities to provide more value through services along with the products' lifetime [...] even more so if the services extend the lifetime*". Baines et al. [5] talk about the potential to decouple environmental pressure from economic growth by focusing on asset use, however, it is argued that the potential environmental benefit may be evaluated only after deep knowledge about customers and products is obtained.

The interviewees, alike some authors, recognized the connection that sustainability, digitalization and servitisation have [16]. Those are perceived as mutually reinforcing concepts for a future-proof business: *"data collection on services and customer use today will enable big data and artificial intelligence solutions in the future"*.

Tactical. The second category of drivers concerns more tangible motives to introduce PSS in a capital good manufacturing company. The reasons to introduce PSS as stated by some of the interviewees are: *"to increase overall equipment effectiveness (OEE) and through services increase availability, performance and quality"* and *"to reduce lost time in changeovers, maintenance, cleaning and start-ups"*. Some authors argue that product efficiency can be increased by PSS on a high level [17], however, these empirical findings dig much deeper into the problematic area.

There are other benefits of PSS as recognized by an interviewee who said: *"Services could contribute to a reduction of waste, energy and water used in production."*, which are the most environmentally impactful actions for an in-use asset. That statement is supported by Kjaer et al. [4], who see PSS as an enabler of resource reduction.

Another tactical driver is to enable the supply of better quality products by feeding back the information obtained through the service interactions with customers, as recognized by Mont [13]. In this way, "*partnerships can be built with suppliers beneficial to all parties",* as stated by an interviewee.

Structure in dealing with service callouts has been recognized by an interviewee who said: *"We should reduce firefighting at customers and have a standard way to deal with it"*. This observation goes in hand with that of another interviewee who said: *"…through services we could learn much more about our warranty cases and win them more often",* which can be tied back to knowing the products' performance and customers' behaviour. Communication with customers about end-of-life product condition was also noted as a driver as it is perceived that many services could be revolved around the provision of circular activities such as upgrade, refurbishment, resale, and recycling.

Operational. Only a couple of operational drivers were elicited for the introduction of PSS through empirical research. Those refer to learning more about wear and critical parts and internal training and procedures for routine service operations such as maintenance and cleaning of products. Finally, one of the interviewees said: *"…if we were our customers, we would not make a product that is difficult or expensive to operate.",* implying that service capabilities that would enable ease and affordability of operation have to first be developed internally before being able to teach customers the same.

Barriers. *Strategic.* The first strategic barrier is closely related to the first strategic driver, a knowledge barrier to the connection between sustainability and services. This difficulty to clearly define offerings, set unambiguous performance indicators and trace the transition is a barrier recognized by numerous authors [12]. One of the interviewees said: *"We do not have a common understanding of sustainability, let alone how services influence it."*. Evaluation of service potential has been also raised by the commentators in previous studies [17, 18]. Another strategic barrier concerns the framing of the offerings for various customer segments and their respective business strategies. One of the interview claims is: *"We have very limited knowledge of our customers' strategies and views on receiving services from us",* a barrier also noted by Adrodegari et al. [7].

A further barrier is the ability to amortize extended payment periods that come with PSS and the viability of investing in the development of PSS offerings rather than other projects. Several interviewees claim that: *"…it is challenging to estimate the financial potential of PSS solutions.",* which is also stressed by numerous authors [3, 18].

Tactical. While the literature recognizes barriers such as the difficulty to fully understand customers' needs [18] and the inaccuracy of predicting customers' usage [17], the findings of this empirical study enunciate these barriers as crucial to the success of the service-related business. Several interviewees stated that the company has very limited knowledge of what service needs do their customers have. An interviewee said: *"We need to observe customers and talk to them more."*. A recurring theme in the interviews was also the lack of knowledge of how exactly customers use the company's products. An interview said: *"We think customers use our products in a certain way, but we don't know with certainty, meaning that we do not know the products' exact performance*". Therefore, it seems that such insights would greatly help in streamlining the capital goods with long lifetimes for ease of use and consequently bring more value. There is potential to capitalize both financially and with reduced environmental impact if exact needs could be embedded in PSS offerings [5].

Standardization of the product portfolio is seen as a prerequisite to servitisation as one of the interviewees pointed out: *"…lack of the product standardization makes it difficult to offer standard services and track and compare their performances."*.

Operational. An evident challenge is the lack of knowledge and capabilities to drive the PSS development process [13]. For capital goods manufacturers, the challenge is to gather and determine data needed that would enable understanding customer needs and product usage insights, and consequently be a basis for more valuable offerings. An interview said: *"We realize the importance of having insights into how customers use our products, but we don't know what data are relevant to measure."*, and another said: *"Even if we had all the possible data, we wouldn't know how to make sense of it."*. Therefore, data analysis skills are seen as pivotal to develop new PSS offerings in a structured way. In practice, as one of the interviewees put it; *"…even the customers might not be able to express their need or how they use the products."*. The question is raised whether it is the customer's provider's role to enable data gathering.

Another concern is the willingness of a customer to share data with the manufacturer. A couple of interviewees stressed the customers' fears of legal and GDPR problems, as also indicated by numerous commentators [15]. A further notable barrier stated by the interviewees is a lack of resources to be proactive about offering combined solutions.

4 Discussion

Results Commentary. Largely similar patterns are recognized when comparing literature and empirical findings about drivers and barriers for the introduction of PSS. Certain exceptions are, however, observable both with respect to drivers and barriers. It is the depth of the empirical study that yields more concrete insights into perceived drivers and barriers in the company. Namely, if compared to literature, this empirical approach identifies many more tactical and operational drivers and barriers. This also seems to be related to the interviewees' position in the company, as they tend to think of operational barriers they would have in their position. That is deemed only natural but very valuable as such interviewees bring out concrete challenges and ideas to overcome them. Strategic employees, on the other hand, see many strategic drivers that are primarily related to sustainability and very few barriers.

It was difficult for managers at the operational level of the organization to find drivers for their actions. It is perceived that the motivation for action comes from a level above, either tactical or strategic. This observation brings even more attention to the importance of the top-down approach and clear communication of the PSS value coming from strategic and down to tactical and operational levels. Most of the drivers as perceived by interviewees were focused on what the company should expect to gain from PSS and only a few on what the customer gains. Furthermore, it is perceived that it most frequently the customer who is the cause of most of the barriers.

The access to the product and the ability to track its performance during the useful life is observed to be of pivotal importance, as this opens opportunities to build services, even on top of an already installed base of products. While PSS is not just a service built on top of the product, which is not inherently designed for it, this type of (so-called "wire-framing") approach is often seen as a way to test the market with new services. It is challenging to carry out product alterations once they are already at the customer, and significant changes would introduce unknown risks after the product is already installed. Therefore, moderate alterations only can be made in this way as pilot projects, in order to gain input to new PSS development projects.

As perceived by the authors, patterns can be observed when considering the interviewees' function in the company. When comparing interview answers, the most conspicuous divergence arose between the answers of interviewees with technical versus non-technical background. This difference primarily manifests in the sharpness of focus on the challenges by the technical staff rather than drivers, and their focus on the operational rather than strategic motives and obstacles. Hence, they weigh different challenges differently according to their technical nature. Another dimension to compare the answers from the interviewees is whether they perform a customer-facing function. Those who interact with customers are more certain that a customer is willing to share data and collaborate than those who do not have direct contact with customers.

The most recurrent theme of the interviews is the importance of knowing the customer and the importance of knowing the use phase of the product, and it is observed as crucial for the provision of PSS offerings. The opportunity to provide value within the lifetime of a capital good is perceived as immense by the interviewees, both financial in terms of savings for customers and earnings for the producer, but also environmental, with proper service and maintenance to extend to products' life and efficiency.

Actions Based on Results. It is considered that the result representation in Fig. 1 may serve as a canvas for drawing a roadmap of the action course for further PSS development. As a first step, practitioners would have to agree on the most important driver for the introduction of PSS. By making such a decision, all the lower-level drivers and barriers can be prioritized, that is, focused on achieving that strategic goal. Hence, even though there are still many barriers, some may be eliminated as tackling them will not bring the company any closer to achieving the strategic goal, and some are mitigated by the clear motivation on why they must be resolved on each level.

As depicted in Fig. 2, a preliminary roadmap can be drawn, connecting the most important drivers with the corresponding barriers starting from the main strategic goal indicated with the red circle. The process is then further guided through tactical and operational drivers and barriers to a single operational action.

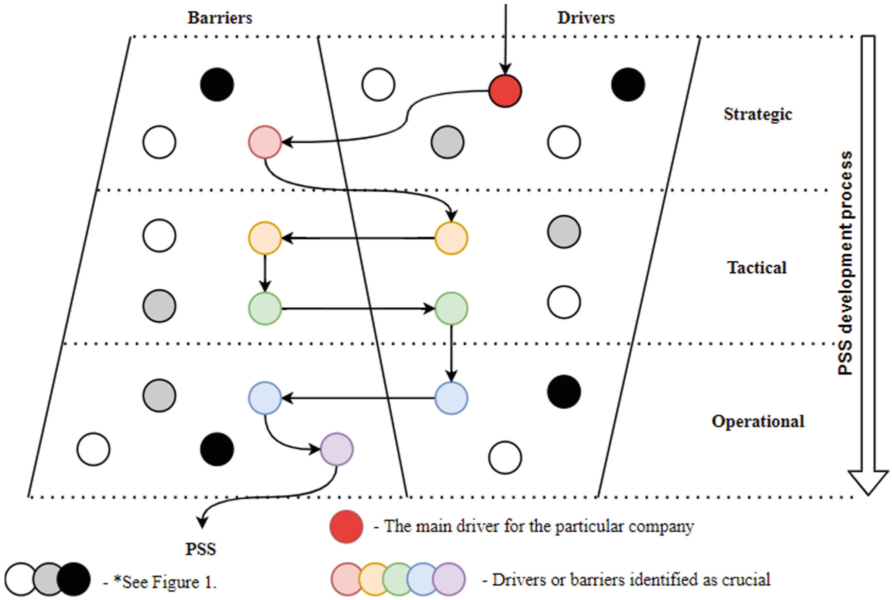

Fig. 2. Focusing the PSS development process with the help of drivers and barriers.

Depending on the impact that the addressing of a particular barrier will have on the main driver, the most impactful barriers may be selected to be solved. As the path progresses towards more operational challenges to solve, more drivers will be evident to the operational personnel, regarding why it is important to address those challenges. It can be said that barriers are translated in a process or the course of action. They serve to create and direct the PSS development process.

For the case company, as per Fig. 2, perceived dominant barriers in relation to the strategic driver of sustainability are the knowledge barriers about the connection between sustainability and service. On a tactical level, this can be translated into a driver that is the introduction of product upgrade services that will contribute to energy savings (yellow driver circle). There are other barriers on the same level, namely, the company has limited knowledge on the current energy performance of the product, consequently, there is a challenge on how to measure the performance after the upgrade (green barrier circle). There is another driver to track the product performance–to find out how customers use the product. Moving into operational drivers (blue driver circle), another motive to introduce a monitoring system would be to enable the gathering of different data points that could, in turn, help with optimizing other factors than the energy use. An operational barrier here is to discern what data is relevant to measure and stemming from it is the competence barrier to analyze the gathered data. Following such a train of thought, as in Fig. 2, it could be deducted that knowing the customer and the products' use phase would have a significant impact on the success of the PSS implementation. Those challenges are easily tied to the traditional view of product development in manufacturing companies, where products are not designed for ease of use and serviceability. Opportunities to address those challenges are possible through mapping user activity cycles, service blueprinting and usage monitoring. Therefore, it seems that the most sustainably potent form of PSS for capital goods manufacturing companies is inseparable from the digitalization process and data gathering.

Limitations. This approach is proposed based on a single case study; thus, it has a very specific application, and it is not possible to draw generic conclusions for all capital goods manufacturing firms. The value of such a study manifests in the depth of insight achievable for an individual practitioner, as well as to showcase the importance of drivers and barriers that were not found empirically to the case company. Further studies in other cases will elicit to what extent the approach might be generalizable. The model depicted in Fig. 2 might be tested by conducting a series of interviews in other companies, as it is done in this study, to elicit drivers and barriers from different levels of the organization. Those can then be used to lay down or streamline the course of action in the process in the PSS development with respect to the company's strategic goals.

5 Conclusion

Instead of focusing on solely top management input, this empirical research brings a 360-degree approach within the company to clarify the pivotal motives and challenges for the introduction of PSS, both from the strategic, tactical and operational levels.

The purpose of such a business-wide investigation of motives and challenges is manifold; to get an understanding of the interaction and viewpoints from different parts of the organization; to elicit and communicate ideas across the organization; to spot previously unforeseen opportunities; not to overlook some of the challenges, and to make more informed and inclusive decisions about the focus of PSS development in the organization. Practitioners may, therefore, replicate this approach to gauge themselves internally before reaching out to the customers having considered internal dialogues.

Different parts of the organization perceive drivers and barriers for the introduction of PSS differently. Various viewpoints seem to be connected to the nature and the seniority of the interviewees' functions, where noticeable differences in answers are observed depending on the technical or non-technical nature of the function and whether the participants were interacting directly with the customers or not.

Guided by the most recurring interviewee observations paired with literature research, further research steps will be the involvement of customers and the data to be gathered from the installed base of the products in the PSS co-development process. The intention is, therefore, to adopt a customer-oriented and data-driven approach motivated by sustainable agenda that would yield the most valuable solutions both for the customer and the PSS provider.

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References

1. de Angelis, R.: Business Models in the Circular Economy: Concepts, Examples and Theory. Palgrave MacMillan, Cham (2018)
2. Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B.: Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. **33**, 308–320 (2016). https://doi.org/10.1080/21681015.2016.1172124
3. Tukker, A.: Eight types of product-service system: eight ways to sustainability? Experiences from suspronet. Bus. Strateg. Environ. **13**, 246–260 (2004). https://doi.org/10.1002/bse.414
4. Kjaer, L.L., Pigosso, D.C.A.A., Niero, M., et al.: Product/service-systems for a circular economy: the route to decoupling economic growth from resource consumption? J. Ind. Ecol. **23**, 22–35 (2019). https://doi.org/10.1111/jiec.12747
5. Baines, T.S., Lightfoot, H.W., Evans, S., et al.: State-of-the-art in product-service systems. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. **221**, 1543–1552 (2007). https://doi.org/10.1243/09544054JEM858
6. Tukker, A.: Product services for a resource-efficient and circular economy-a review. J. Clean. Prod. **97**, 76–91 (2015)
7. Adrodegari, F., Bacchetti, A., Saccani, N., et al.: The transition towards service-oriented business models: a European survey on capital goods manufacturers. Int. J. Eng. Bus. Manag. **10**, 1847979018754469 (2018). https://doi.org/10.1177/1847979018754469
8. Baines, T.S., Lightfoot, H.W., Benedettini, O., Kay, J.M.: The servitization of manufacturing: a review of literature and reflection on future challenges. J. Manuf. Technol. Manag. **20**, 547–567 (2009)
9. Dyer, W.G., Wilkins, A.L.: Better stories, not better constructs, to generate better theory: a rejoinder to eisenhardt. Acad. Manag. Rev. **16**, 613–619 (1991). https://doi.org/10.5465/amr.1991.4279492
10. Šarančić, D., Pigosso, D.C.A., McAloone, T.C.: Investigating drivers and barriers for the development of Product-Service Systems in capital goods manufacturing companies. In: Proceedings of the International Conference on Engineering Design, ICED, Gothenburg (2021)
11. Robson, C., McCartan, K.: Real World Research, 4 Edn. Wiley, Chichester (2016)
12. Martinez, V., Bastl, M., Kingston, J., Evans, S.: Challenges in transforming manufacturing organisations into product-service providers. J. Manuf. Technol. Manag. **21**, 449–469 (2010). https://doi.org/10.1108/17410381011046571
13. Mont, O.K.: Clarifying the concept of product-service system. J. Clean. Prod. **10**, 237–245 (2002). https://doi.org/10.1016/S0959-6526(01)00039-7
14. Ulaga, W., Reinartz, W.J.: Hybrid offerings: how manufacturing firms combine goods and services successfully. J. Mark **75**, 5–23 (2011). https://doi.org/10.1509/jm.09.0395

15. Kowalkowski, C., Kindström, D., Gebauer, H.: ICT as a catalyst for service business orientation. J. Bus. Ind. Mark **28**, 506–513 (2013). https://doi.org/10.1108/JBIM-04-2013-0096
16. Hallstedt, S.I., Isaksson, O., Rönnbäck, A.A.Ö.: The need for new product development capabilities from digitalization, sustainability, and servitization trends. Sustain **12**, 1–26 (2020). https://doi.org/10.3390/su122310222
17. Meier, H., Roy, R., Seliger, G.: Industrial product-service systems-IPS2. CIRP Ann-Manuf. Technol. **59**, 607–627 (2010). https://doi.org/10.1016/j.cirp.2010.05.004
18. Oliva, R., Kallenberg, R.: Managing the transition from products to services. Int. J. Serv. Ind. Manag. **14**, 160–172 (2003). https://doi.org/10.1108/09564230310474138

Prevention of Failures in the Footwear Production Process by Applying Machine Learning

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Abstract. At present, the handcrafted footwear sector is affected by the high competitiveness due to the increasing automation of companies. In this sense, in order to improve its competitiveness, a system was proposed to predict the failures of a production system and to carry out preventive maintenance actions. Samples were taken from 25 productions and 7 activities were established: cutting, stitching, pre fabrication, final preparation, gluing, assembly and finishing. The company produces batches of 90 pairs per day, with a standard time of 274.53 min and a promised productivity of 1.8. A support vector machine model was developed to predict the possible failures of the process taking as a reference the standard time of each stage. Finally, the results allow predicting the faults to optimise the production process by applying Support Vector Machine (SVM).

Keywords: Production · Shoes · Support vector machine

1 Introduction

1.1 Background

Companies in the footwear industry are seeking to become more competitive in order to remain viable. More efficient processes are being researched in the fields of administration and manufacture in order to ensure their sustainability [1], and pervasive changes are being implemented in order to respond to the demands of a global market [2, 3]. In this vein, the revolution in the footwear industry represents a huge challenge, requiring the determination of its strengths and weaknesses to foster its productivity [4].

Industries must respond favorably to changes in the market with adjustable technologies and tools that enable the reduction of delivery times and improve productivity in small and medium companies [5, 6]. With these applications, mass production can be adapted to flexible production, where identifying the critical points is crucial to optimize

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the process [7]. The productive processes have evolved at a fast pace, developing the traditional model into one that implements circular economy [8].

The footwear industry is characterized by continuous production, consuming resources in proportion to the production volume, thus requiring the management of refuse and its disposal [9]. A direct relationship exists between productivity and optimal spending of resources, therefore, identifying the activities that do not add value and influence the system negatively is of vital importance [10]. This can be done via two different approaches: the first uses the econometric technique, that analyzes inputs and outputs empirically; while the second uses Malmquist's data envelopment analysis (DEA) [11].

Performing an analysis of productivity and related costs of the industrial sector is necessary to establish the baseline production capacity and organize effective resource management. Studies done in the context show that the existence of restrictions that obstruct the production system reduce the efficiency and productivity of a company [12, 13]. In manufacturing industry, processes must be standardized in order to establish a baseline and then propose improvements to ensure the company's sustainability, which is done via the measurement of the different times as described by Niebels [14].

The Latin-American footwear industry tries to improve and optimize the duration of the productive process constantly [15]. At a regional level, it is of great interest that small companies improve their processes [16], promoting innovation and modernization of the processes to encourage international competitiveness [17]. To reach this goal, studies have been performed to determine productivity, competitiveness [18], and job satisfaction [19].

One of the most studied resources to improve competitiveness in companies is the manufacturing time. Several methods to approach the issue exist, such as: study with a chronometer, study of the general efficiency of a machine to minimize the time of a cycle, determination of the standard time in textile industry to find the efficiency of a system, and using the Methods-Time Measurement (MTM) to analyze a primary model in an assembly line, among others [20].

1.2 Related Work

The implementation of Internet of Things technologies (IoT) is one of the most important changes in the New Industrial Revolution. The IoT makes the measurement of production times in real time possible, thus helping optimize processes and avoid interruptions, while also being able to predict faults and anomalies [21, 22]. For this study, a support vector machine (SVM) was used as a fault diagnostic tool [23].

SVMs are classifiers to diagnose faults and require small amounts of training samples [24]. These classifiers combined with other methods allow industrial applications to predict faults [25–27].

Other studies have analyzed the efficacy of classifiers with artificial neural networks (ANN) and SVM to diagnose faults in bearings, showing that SVM is more efficient than ANN [28–30].

The aim of the present study consists in creating an SVM model to predict potential faults, based on the determination of the standard time of a footwear manufacturing process of a factory in Ecuador. Using the standard time as a reference, several optimization measures to increase productivity will be evaluated. The rest of this contribution is organized as follows: Sect. 2 will present the methods used in this investigation, Sect. 3 will describe the results, and Sect. 4 will present the conclusions of the study.

2 Method

2.1 Layout of the Factory

The Tungurahua province in Ecuador is the source 44% of all the country's footwear production [31]. Within this province, in the city of Ambato, lies the company studied in this article, Ludwing Fer. The company's main product during its 28 years of existence has been formal leather footwear. As it can be observed in Fig. 1, the layout of the factory is linear.

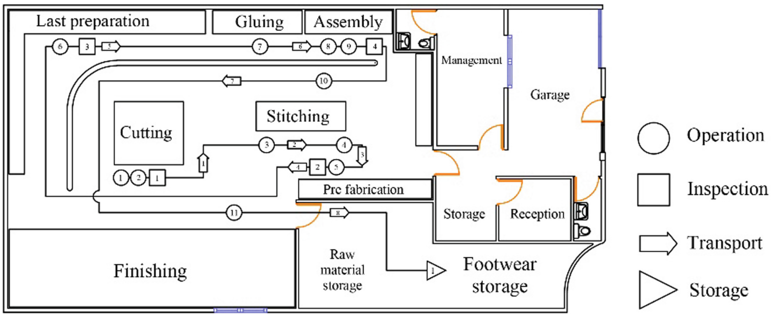

Fig. 1. Layout of the ludwing fer factory.

The company produces on average 90 pairs of shoes every day, with standard production time of 274,53 min. The factory employs local manpower and machinery that it is deemed 'optimal' for the present moment.

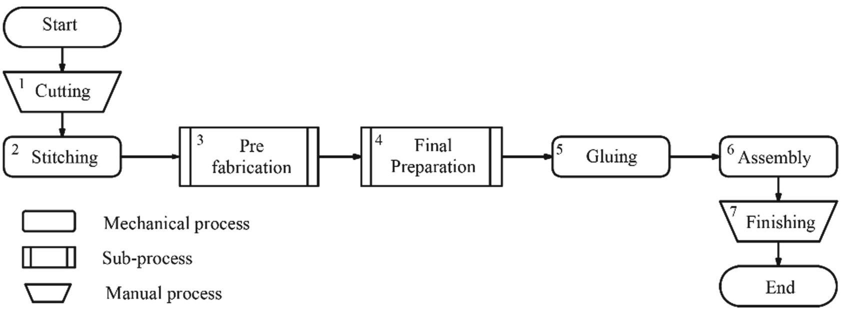

Fig. 2. Production process of the company.

Figure 2 shows the main stages of the footwear manufacturing process. The production process consists of seven stages: cutting, stitching, pre-fabrication, final-preparation, gluing, assembly and final storage. This process is a mixed manual and mechanical process, as the company is an artisanal one.

2.2 Algorithm

The aim of this study consists in defining a statistic measurement in order to determine the factors that influence the efficiency of footwear manufacturing process. The measurement of the efficiency of a company is a complex and multidimensional process involving the characteristics of the production process, the context and its environment. Several definitions of industrial efficiency exist, but all of them agree that one of the most representative indicators is the standard time that measure quantitatively the achievements of a company. Another indicator of efficiency is the productivity index, which will also be considered in this article [32].

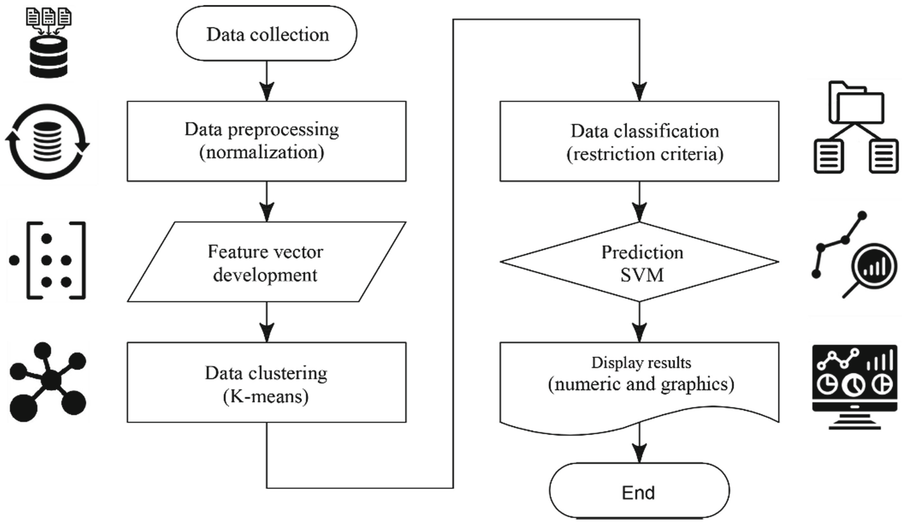

Fig. 3. Conceptual flowchart of the process

The conceptual flowchart shown in Fig. 3 summarizes the process. It consists of five steps: data collection, data processing (normalization), vector generation (arithmetic mean), data grouping, function classification (restrictions), and predictions with SVM.

The k-means method was used to classify a group of data related to the added-value fluxes of the process, and the results of this analysis will be used to improve production times.

In order to find the minimum number of observations needed for every production step so that the sample is representative, the usual formula used in statistics is employed (see Eq. 1).

$$n = \left(\frac{40\sqrt{\left(c \sum x^2\right) - \left(\sum x\right)^2}}{\sum x} \right)^2 \tag{1}$$

Where n is the number of observations, c is the number of initial observations, and x is the value of these observations.

The characteristics of the process are integrated in a vector containing quantitative data such as: number of products, standard times, and productivity. Equation 2 represents the production index z. This is a vector that contains the standard times of each phase of the production process and other parameters. To calculate the value of z, a geometric or arithmetic mean is performed.

$$\mathrm{z} = (C_u, T_{Ei}, \ldots, T_{En,} P_m, P_M)^{\mathrm{T}}, \; i = 1, 2, 3, \ldots, n \tag{2}$$

Where C_u is the number of finished products, T_{Ei} is the standard time of the process, P_m is the monofactorial productivity, and P_M is the multifactorial productivity.

Table 1. Prediction algorithm

Algorithm	Prediction
Input:	$\boldsymbol{z} = (C_u, T_{Ei}, \ldots, T_{En,} P_m, P_M)^T, \quad i = 1,2,3,\ldots,n$
Output:	Prediction
	Initialize - K Clusters with their centroids of $\mu_1, \ldots, \mu_k$ randomly
	While not converge:
	for i in range $(dataset)$:
	$C_k = argmin\|x_i - \mu_k\|^2$
	for j in range $(\boldsymbol{k})$:
	$\mu_j = \frac{1}{N}\sum_{i=1}^{N} x_i$
	end while
	Initialize – classification with restriction criteria
	if $Times \leq 1$ and $Produc \leq 0.7$
	Type A
	Else
	$Times > 1$ and $Produc > 0.7$
	Type B
	end classification
	Initialize – prediction SVM
	Model (Kernel = 'linear') - $f(x) = sgn(w^T x + b)$
	Model (Kernel = 'poly') - $k(x_i, y_j) = (x_i \cdot y_j)^d$
	Input Data for prediction
	$\boldsymbol{z}^* = (C_u, T_{Ei}, \ldots, T_{En,} P_m, P_M)^T, \; i = 1,2,3,\ldots,n$ sample data
	end prediction

Table 1 shows the algorithm created for this research. The first part creates clusters with their centroids and calculates the statistical values of the production. The second classification with restriction criteria. The third part generates a prediction with SVM, which includes the prediction functions kernel from the Python suite.

In order to train the algorithm, statistical measurements were calculated: mean $\bar{x}$, standard deviation σ, maximum value (max) and minimum value (min) of the production phases. From the results of the statistical measurements it can be inferred that the averages of the measurements allow a classification of the productions in type A and B. Type A are productions that are considered negative because the production line has failures (delays, unscheduled stops, etc.) and type B are considered productions that are in normal conditions. Finally, with the data of the productions separated into two types, an SVM model will be built, so that it can predict if a production will need preventive maintenance.

The multifactorial productivity compares the amount of production with the consumption in terms of raw materials, energy, manpower, capital, and services.

3 Results

This section analyses the results obtained from the algorithm. The data was collected for the whole production process, with 25 readings in 126 steps comprising the 7 main production phases (thus yielding 3150 durations in total). These readings were the starting point from which the algorithm was trained.

Table 2. Sample data set

Year	Number of samples	Number units produced	Standard time [min]
2019	25	2165	6505

Table 2 shows a summary of the samples taken in 2019. There were 25 measurements, the total production was 2165 units and the standard time was 6505 min.

Figure 3 shows the relationship between the number of units and the multifactorial productivity of the 25 readings with 126 steps each one.

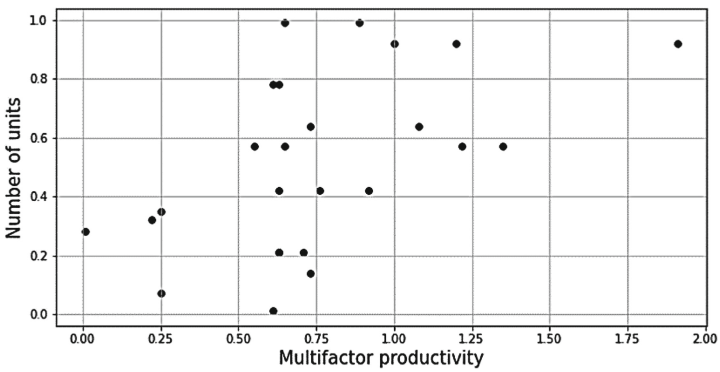

Fig. 4. Number of units vs. multifactorial productivity.

A Python script was written in order to perform cluster analysis though the elbow method and K-means. From this, it was found that the number of clusters was k = 7. Figure 4 shows the results of the analysis, where the relationship between the number of units produced and the productivity index *z* is shown.

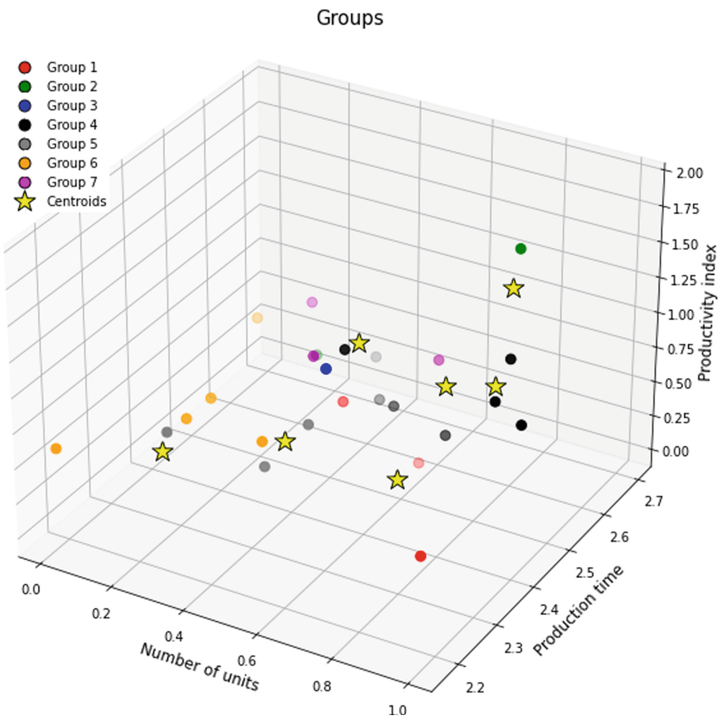

Fig. 5. Number of units, production time and productivity index, with data points grouped in clusters, each one with its centroid.

From this analysis, it can be determined that the mean of cluster 5 has the highest productivity index, and is thus the longest (due to the manual operations) (Fig. 5).

3.1 Classification

The restrictions applied to find the relationship between the number of units and the productivity index can be classified as follows:

Type A, labeled "−1", includes all productions that fulfill

$$z \leq 1 \text{ and } C_u \leq 0.7 \tag{2}$$

Type B, labeled "1", includes all productions that fulfill

$$z \leq 1 \text{ and } C_u \leq 0.7 \tag{3}$$

Table 3. Statistical measures for types A and B

Statistical measures	Type A			Type B		
	C_u	T_E	z	C_u	T_E	z
$\bar{x}$	1.58	2.37	0.76	1.53	2.44	0.75
σ	0.31	0.10	0.16	0.23	0.12	0.43
min	1.11	2.17	0.61	1.11	2.17	0.01
max	1.98	2.44	1.00	1.90	2.70	1.91

This classification yields a group of 5 Type A productions, and another group of 20 Type B productions.

Table 3 shows the statistical measures of the cutting phase C_u, standard times T_E and productivity index z. These statistical measurements are the 25 measurements taken in 2019 that were used to train the algorithm, thus implementing the classifier for type A and B productions.

3.2 Prediction

Finally, in order to predict the number of faults, an algorithm for a support vector machine (SVM) is used. Several tests are performed with the algorithm using new measures of 10 productions, detecting 4 faults during the production process.

Table 4. Prediction for types A and B

Production	Lineal model		Polynomial model	
	Type A	Type B	Type A	Type B
1	1		1	
2	1		1	
3	1		1	
4		−1		−1
5		−1		−1
6		−1		−1
7		−1		−1
8	1		1	
9	1		1	
10	1		1	

Table 4 shows the fault prediction results. A "−1" represents a possible fault during the process due to a lack of fulfilment of the base criteria. Therefore, the results can predict possible faults or delays with precision. The failures were detected in the cutting area and were caused by regulation failures and loss of the cutting edge of the blades. The mathematical models "linear" and "poly" have yielded the same results and the detected faults can be mostly linked to the manual operations.

4 Discussion

The results displayed in the previous sections show the potential of data mining for the continuous improvement of production processes. The Python software developed in this article is flexible and can predict faults in numeric and graphic forms. With this information, potential faults can be identified quickly, as well as inefficient workers or excessive energy consumption.

Quantitative studies have been conducted in footwear companies in Ecuador, where new technologies are being researched to increase overall efficiency [33]. This article proposes a method capable of systematizing the information of the production process in order to prevent failures. The failures are detected early via an algorithm where the production times of each day are inputted. However, it must be ad-mitted the algorithm presents some limitations, since the process is manual and the instruments for acquisition and control in real time have yet to be implemented.

The method is flexible and can focus on a single stage of the process deemed high-risk. The models and configuration developed with Python are complex processes that create automatic learning solutions without needing programming knowledge.

Compared to other algorithms, it requires less preprocessing because its configuration accepts an input vector containing all the characteristics of the process. However, it has also limitations, such as the difficulty in codifying the restrictions for every production process.

5 Conclusions

The present study developed a technique to evaluate the production process of a factory manufacturing semi-handcrafted footwear. A k-means model was applied and the processes were classified with quantitative restrictions. The process classification was based on restrictions that help interpret the production times of each one, and thus be able to predict faults.

The predictions were obtained with machine-learning Python algorithms supervised first by linear model (kernel = 'linear'), and later by a polynomial model (kernel = 'poly'), with both models yielding similar results. The models are fast, flexible and easily generalizable, which makes them suitable tools to help analyze the collected data during the different stages of the production process. The new process can also estimate the efficiency of new workers and thus help prepare strategies to improve their productivity.

From this study, it was determined that the standard time for a worker to produce 90 pairs of shoes every day was 274 min per pair, using normal tools, machinery and conditions. Thus, the monofactorial productivity is 8.18 pairs/worker, while the multifactorial productivity is 1.8.

The use of automatic learning in shoemaking processes offers the possibility to evaluate and analyze process data and improve production times. However, this will first require an investment in Internet of Things (IoT) technology in order to modernize the company in question and implement real-time data collection.

References

1. Calderón-Andrade, R., Hernández-Gress, E.S., Montufar Benítez, M.A.: Productivity improvement through reengineering and simulation: a case study in a footwear-industry. Appl. Sci. **10**(16), 5590 (2020). https://doi.org/10.3390/app10165590
2. Pla-Barber, J., Villar, C., Benito-Sarriá, G.: Configurational theory in traditional manufacturing industries: a new model of high-performing small and medium-sized enterprises. Sustainability **12**(17), 6818 (2020). https://doi.org/10.3390/su12176818
3. Adulyanukosol, A., Silpcharu, T.: Footwear design strategies for the Thai footwear industry to be excellent in the world market. J. Open Innov. Technol. Mark. Complex. **6**(1), 5 (2020). https://doi.org/10.3390/joitmc6010005
4. Varela, S.C., Santamaría, J.L., Pilamunga, M.: Cultural identity in the productive matrix: a challenge for Ecuadorian footwear. In: Margalina, V.-M., Lavín, J.M. (eds.) Management and Inter/Intra Organizational Relationships in the Textile and Apparel Industry, pp. 200–218. IGI Global, Hershey (2020)
5. Nallusamy, S., Saravanan, V.: Enhancement of overall output in a small scale industry through VSM, line balancing and work standardization. Int. J. Eng. Res. Africa **26**, 176–183 (2016). https://doi.org/10.4028/www.scientific.net/JERA.26.176
6. Saravanan, V., Nallusamy, S., George, A.: Efficiency enhancement in a medium scale gearbox manufacturing company through different lean tools - a case study. Int. J. Eng. Res. Africa **34**, 128–138 (2018). https://doi.org/10.4028/www.scientific.net/JERA.34.128
7. Suganthini Rekha, R., Periyasamy, P., Nallusamy, S.: An optimized model for reduction of cycle time using value stream mapping in a small scale industry. Int. J. Eng. Res. **27**, 179–189 (2016). https://doi.org/10.4028/www.scientific.net/JERA.27.179
8. Turner, C., et al.: Sustainable production in a circular economy: a business model for re-distributed manufacturing. Sustainability **11**(16), 4291 (2019). https://doi.org/10.3390/su11164291
9. Subic, A., Shabani, B., Hedayati, M., Crossin, E.: Capability framework for sustainable manufacturing of sports apparel and footwear. Sustainability **4**(9), 2127–2145 (2012). https://doi.org/10.3390/su4092127
10. Rahul, S.M., Arvind, B., Sarbjit, S., Anish, S.: Productivity gains through standardization-of-work in a manufacturing company. J. Manuf. Technol. Manag. **30**(6), 899–919 (2019). https://doi.org/10.1108/JMTM-07-2017-0151
11. Zrelli, H., Alsharif, A.H., Tlili, I.: Malmquist indexes of productivity change in Tunisian manufacturing industries. Sustainability **12**(4), 1367 (2020). https://doi.org/10.3390/su12041367
12. Reyes, J., Aldas, D., Alvarez, K., García, M., Ruíz, M.: The factory physics for the scheduling: application to footwear industry (2017)
13. Arredondo-Soto, K.C., Realyvasquez-Vargas, A., Maldonado-Macías, A.A., García-Alcaraz, J.: Impact of human resources on remanufacturing process, internal complexity, perceived quality of core, numerosity, and key process indicators. Robot. Comput. Integr. Manuf. **59**, 168–176 (2019). https://doi.org/10.1016/j.rcim.2019.04.004

14. Realyvásquez-Vargas, A., Arredondo-Soto, K.C., Blanco-Fernandez, J., Sandoval-Quintanilla, J.D., Jiménez-Macías, E., García-Alcaraz, J.L.: Work standardization and anthropometric workstation design as an integrated approach to sustainable workplaces in the manufacturing industry. Sustainability **12**(9), 3728 (2020). https://doi.org/10.3390/su12093728
15. Reyes, J., Alvarez, K., Vasquez, R.: Dynamic buffer management for raw material supply in the footwear industry. J. Ind. Intell. Inf. **4**(1) (2015). https://doi.org/10.12720/jiii.4.1.1-8
16. Ortiz, V.K., Caicedo, Á.J.: Procedimiento para la programación y control de la producción de una pequeña empresa de calzado. Sci Tech **19**, 377–384 (2014)
17. Alzate, B.A., Hurtado, J.B., Lopez, L.F.M.: Implementación de herramientas para el diagnóstico de innovación en una empresa del sector calzado en Colombia. RAI Rev Adm e Inovação **12**(3), 310–329 (2015). https://doi.org/10.11606/rai.v12i3.100946
18. Bonilla, Y.M.B., Sánchez, J.Z.M.: Medicion de la productividad y competitividad sector de la industria del calzado en la ciudad de Bogota DC. ANFECA, Mexico DF, Mexico (2013)
19. Vargas Téllez, J.A.: Organización del trabajo y satisfacción laboral: un estudio de caso en la industria del calzado. Nov. Sci. **4**(7), 172–204 (2012)
20. Ghafoorpoor Yazdi, P., Azizi, A., Hashemipour, M.: A hybrid methodology for validation of optimization solutions effects on manufacturing sustainability with time study and simulation approach for SMEs. Sustainability **11**(5), 1454 (2019). https://doi.org/10.3390/su11051454
21. Tomiyama, T., Moyen, F.: Resilient architecture for cyber-physical production systems. CIRP Ann. **67**(1), 161–164 (2018). https://doi.org/10.1016/j.cirp.2018.04.021
22. Puchkova, A., McFarlane, D., Srinivasan, R., Thorne, A.: Resilient planning strategies to support disruption-tolerant production operations. Int. J. Prod. Econ. **226**, 107614 (2020). https://doi.org/10.1016/j.ijpe.2020.107614
23. Ge, M., Du, R., Zhang, G., Xu, Y.: Fault diagnosis using support vector machine with an application in sheet metal stamping operations. Mech. Syst. Signal Process. **18**(1), 143–159 (2004). https://doi.org/10.1016/S0888-3270(03)00071-2
24. Liang, J., Du, R.: Model-based fault detection and diagnosis of HVAC systems using support vector machine method. Int. J. Refrig. **30**(6), 1104–1114 (2007). https://doi.org/10.1016/j.ijrefrig.2006.12.012
25. Song, W., Xiang, J.: A method using numerical simulation and support vector machine to detect faults in bearings. In: Proceedings of the 2017 International Conference on Sensing, Diagnostics, Prognostics, and Control, SDPC 2017, vol. 2017, pp. 603–607, December 2017. https://doi.org/10.1109/SDPC.2017.118
26. Hu, R.L., Leahy, K., Konstantakopoulos, I.C., Auslander, D.M., Spanos, C.J., Agogino, A.M.: Using domain knowledge features for wind turbine diagnostics. In: Proceedings of the 2016 15th IEEE International Conference on Machine Learning and Applications, ICMLA 2016, pp. 300–305, January 2017. https://doi.org/10.1109/ICMLA.2016.172
27. Shi, X., Zhu, L.: Fault line detection of leakage protection system of mine based on rough sets and support vector machine. In: Proceedings of 2012 3rd International Conference on Digital Manufacturing and Automation, ICDMA 2012, pp. 402–405, (2012). https://doi.org/10.1109/ICDMA.2012.96
28. Tyagi, S., Panigrahi, S.K.: A DWT and SVM based method for rolling element bearing fault diagnosis and its comparison with Artificial Neural Networks. J. Appl. Comput. Mech. **3**(1), 80–91 (2017). https://doi.org/10.22055/jacm.2017.21576.1108
29. Huang, J., Di Troia, F., Stamp, M.: Acoustic gait analysis using support vector machines. In: ICISSP 2018-Proceedings of the 4th International Conference on Information Systems Security and Privacy, vol. 2018, pp. 545–552, January 2018. https://doi.org/10.5220/0006730705450552

30. Vera-Rodriguez, R., Lewis, R.P., Mason, J.S.D., Evans, N.W.D.: A large scale footstep database for biometric studies created using cross-biometrics for labelling. In: 2008 10th International Conference on Control, Automation, Robotics and Vision, ICARCV 2008, pp. 1361–1366 (2008). https://doi.org/10.1109/ICARCV.2008.4795721
31. Reyes-Vasquez, J.P., Aldas-Salazar, D.S., Morales-Perrazo, L.A., Garcia-Carrillo, M.G.: EvaluaciÃ\textthreesuperiorn de la capacidad para montaje en la industria manufacturera de calzado. Ing. Ind. **37**, 14–23 (2016)
32. Hitomi, K.: Efficiency analysis of Japan's industry and manufacturing. Technovation **24**(9), 741–748 (2004). https://doi.org/10.1016/S0166-4972(02)00151-7
33. Reyes, J., Alvarez, K., Martínez, A., Guamán, J.: Total productive maintenance for the sewing process in footwear. J. Ind. Eng. Manag. **11**(4), 814–822 (2018). https://doi.org/10.3926/jiem.2644

Achieving Responsive and Sustainable Manufacturing Through a Brokered Agent-Based Production Paradigm

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Abstract. Since the 1980s society has been largely satisfied with modern manufacturing's production practice. We are able to develop supply chains that can produce today's highly complex and advanced products and are able to scale mass production to meet much of society's demands.

However, our growing reliance on a constrained set of production practices leaves society exposed when societal conditions drastically change (e.g., COVID-19). Mass-customisation also suggests that the future manufacturing landscape will be far more volatile requiring a response that cannot be achieved today. Sustainable manufacturing is also of prominent and critical importance, and a reliance on other nation's production capabilities has concerned many nations potentially leaving them exposed during trade negotiations and diplomacy.

While concerns exist, the rapidly maturing field of Additive Manufacturing (AM) and its highly distributed and diverse nature may be able to alleviate them. If we can broker it effectively, AM can come together as one to tackle local, regional, national, and international needs. In this paper, we take a closer look at the drivers that are requiring us to re-think production practice. This is followed by a proposition that effective brokering of AM could mitigate the drivers. The paper then summarises the work the manufacturing community needs to perform in order to make it a reality.

Keywords: Brokering · Additive manufacturing · Agent-based manufacturing · Responsive manufacturing · Mass-customisation · Production constraints · Big Demand · Sustainable production · COVID-19

1 Introduction

Production is a complex multi-faceted problem requiring deep-domain knowledge of demand, manufacturing capability, logistics, and national/international business models and policies. Over the years, modern production practices such as batch, mass and just-in-time, have become stalwart, but new societal drivers are bringing its ability to meet all

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of our production needs into question leading many to ask if we have become complacent and over-reliant on them [1].

COVID-19 is one such example that has exposed some of the gaps in our production practice. Demand rapidly changed from products such as cars and fashion clothing, to food, toilet roll, Personal Protective Equipment (PPE), ventilators and remote-working equipment, with highly localised spikes in demand as lockdown regimes cascaded and tightened across the world. Manufacturing's response to the rapid change proved mixed with dominant and highly developed production practices struggling and, in some cases, being totally disrupted. While this is just one example, it is systemic of a wider set of drivers that are requiring us to re-think production practice and what, if any, additions are required.

This paper's contribution is in unpacking the drivers that are requiring us to re-think production practice. The paper then proposes that a brokered agent-based production paradigm using AM and made deployable at local, regional, national and international levels could meet these drivers. The result of which is an elicitation of the work that the manufacturing community needs to perform to make this a reality.

The paper continues by detailing the review that has been performed to unpack the drivers for production practice change (Sect. 2). This is followed by a proposition to meet these drivers via a brokered agent-based production paradigm using results from academic literature to evidence its potential (Sect. 3). The paper then discusses the results and outlines the future work that the design and manufacturing research community needs to do to realise the paradigm and meet the drivers (Sect. 4). The paper concludes by highlighting the key findings from the review and preliminary work into brokering AM (Sect. 5).

2 Drivers for Responsive and Sustainable Manufacturing

The development of the drivers involved a review of popular media (BBC, newpapers), trade magazines and academic articles through a series of Google and Google Scholar searches. The searches included "Challenges in production engineering", "lessons learned from the COVID-19 pandemic", "2020 Production Landscape", "Responsive Manufacturing" and "Sustainable Manufacturing". Articles from the first couple of pages of results were collated from the searches. Searches were performed in October 2020. With the literature defined, the researchers followed a four-step thematic analysis: 1) Familiarisation; 2) Coding; 3) Review and Define Themes; and 4) Report Themes.

Step 1 is where the researchers become familiar with the dataset via quick reads of a subset of documents from the corpus. Step 2 is to then read the literature in more detail and code the documents with key features that relate to the thematic analysis' intention. In our case, the researchers coded the documents to identify drivers for new production practice. Step 3 brings the researchers together to review their codes, identify matches and then group them under themes. Stage 4 then reports the themes where the coded documents are used to reference and evidence the theme. The section continues with a presentation of the elicited themes.

2.1 Driver 1. Big Demand

The first theme concerns production's ability to respond to significant, volatile, and rapid changes in the volume, variety, and location of society's product demand (Fig. 1); a theme that we have termed 'Big Demand'. COVID-19, Brexit, Disaster Response, Global Financial Crises, and War are all events that resulted in Big Demand scenarios which led to production systems failing to respond quickly [2].

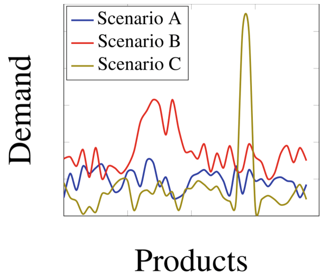

Fig. 1. Illustration of societal Big Demand profiles.

Considering COVID-19 as the most recent example, we have observed an ineffectual response from many modern production systems, with society's demands changing from, for example, vehicles and fashion clothing to Personal Protection Equipment (PPE), ventilators and remote working equipment. Many mass production systems, such as the automotive sector, simply could not meet Big Demand as they have been optimised over many decades for a particular product or set of products [2]. This resulted in many production systems remaining dormant. Some accounts revealed it took production approximately three months to re-configure, ramp up and deliver the suitable levels of PPE to meet society's demands [3].

Mass-customisation is also driving Big Demand scenarios where consumer trends change even more rapidly with even greater variety and locality. However, it has been shown that productions' answer to mass-customisation is to increase the cost of the product offered to the consumer in order to accommodate the production changes necessary through current practice [4, 5]. [6] highlight manufacturing firms' governance structure and production practice needs to be re-framed in order to accommodate mass-customisation as it cannot be simply appended to existing practice. Therefore, Driver 1 is in meeting Big Demand.

2.2 Driver 2. Sustainable Production

Sustainable Design & Manufacture is a top priority for nations with many allocating funds to specifically target sustainability through research and innovation pathways [7]. It has been a long-term goal for society with research dating back to the beginning of the millennium [8]. Extended global supply chains have enabled us to produce products at the demand, scale and cost required by society but has only been achievable due to the unequal international dimensions of austerity [9, 10]. [11, 12] demonstrate that our technical capability to assess the environmental impact of a products' lifecycle has continued to improve but the motivation for businesses to act on this information is still a challenge. And [13] highlights that sustainable production is not an instant change but one of continuous process improvement. This leads to Driver 2, which is the continued need and desire to produce sustainably.

2.3 Driver 3. Production Constraints

Global events have also contributed to highly dynamic and distinct constraints on production, such as social distancing (COVID-19) and trade agreements (Brexit, America vs. China). They also impact society at local community, regional and national levels. For example, the UK's COVID-19 tier system and local government initiatives continually changed the landscape of what employees and employers could ask of their employees. The World Trade Organisation anticipated world trade would fall between 13% and 32% due to the unique constraints placed of COVID-19 suggesting significant changes in the global supply landscape [14].

The highly optimised and controlled production systems are unable to respond quickly enough to such dynamic and distinct constraints, if only because by the time they are modified to meet the new constraints they will have changed again. This is a particular challenge for multi-process manufacturing techniques where the constraints could impact any one or more areas of the process resulting in significant downstream delays. These constraints are also unlike any other day-to-day operational constraints (e.g., day-late deliveries of components) that have been researched before. Driver 3 is therefore to enable production systems to accommodate highly dynamic and distinct production constraints in order to maintain supply (Fig. 2).

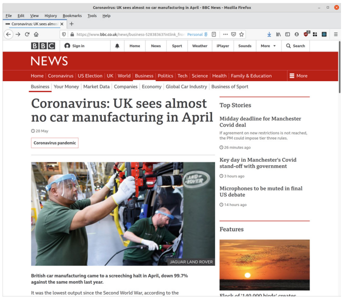

Fig. 2. Production systems constrained by highly dynamic and distinct constraints [2].

2.4 Driver 4. Manufacturing Independence

Modern production practice has resulted in large, developed nations – America, China, EU, Japan, South Korea, India – providing production capability that developed smaller (e.g., UK and Switzerland) and developing nations would not have had access to (Fig. 3). This is due, in part, to manufacturing facilities that can produce at scale, unequal international dimensions of austerity and supply chain logistics.

Whilst access rather than ownership may be advantageous in many economic climates, production independence remains a vision for many nations (e.g., re-shoring) and particularly for fundamental products such as food, clothes, medicines etc. [16, 17]. This has been exacerbated by Drivers 1 & 3 where a nations' reliance on other nations' manufacturing capability leaves them vulnerable and without the capability to combat their national needs [18].

There are also particular benefits for developing countries as it has argued that current production practices require and exacerbate poverty in order for them to function as they depend upon international dimensions of austerity remaining unequal so that they continue to be profitable [19, 20]. They also often exclude property ownership and have a poor track record for boosting living standards in developing countries [9]. Driver 4 is therefore for production systems that can facilitate local, regional, and national manufacturing independence.

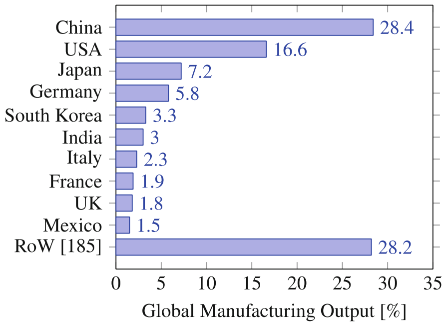

Fig. 3. Distribution of production [15].

2.5 Summary

In summary, the thematic analysis reveals four drivers for new production practice that can complement existing practice in meeting the increasingly varied production needs of society. The drivers are for productions systems that can:

1. Respond to Big Demand.
2. Enable sustainable production.
3. Adapt to highly dynamic and distinct manufacturing constraints.
4. Facilitate local, regional and national manufacturing independence.

3 A Brokered Agent-Based Production Paradigm

Having defined the drivers for new production systems, the paper continues by proposing a production system based upon Additive Manufacturing (AM) literature that has the potential to meet them. The authors propose that a brokered agent-based production paradigm would support a sustainable and responsive manufacturing future (Fig. 4) and is justified in the following sections.

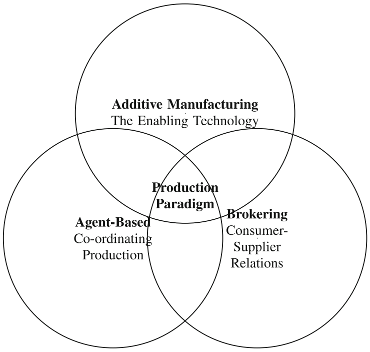

Fig. 4. Brokered agent-based production paradigm

3.1 Additive Manufacturing – the Enabling Technology

The underlying characteristics of AM offer the potential to directly impact all four drivers. AM was the manufacturing technology that government/frontline services turned to during the initial stages of lockdown to meet national demand (Driver 1 – Big Demand). This was attributed to: the ease at which innovators can design for AM and in turn have a manufacturable product in record time; interoperability of manufacturing code enabling products to be produced on all manner of AM; and the ability for AM to switch product production in an instant [21]. The single process, and often machine, required to produce a component also provides an attractive de-centralised mechanism where individual machines can work on a variety jobs for an organisation and can be rapidly adjusted to support an organisation's demands. It also has the potential to expose the supply chain as AM's diversity enables organisations to support a greater variety of jobs.

In terms of Driver 2 (Sustainable Production), [22] has shown AM to improve sustainability outcomes in business operations. Desktop AM technologies have also provided an affordable means to manufacture parts in homes and communities and in doing so, has been shown to have sustainability benefits, principally through the near elimination of supply chains [23]. AM enables businesses to work socially responsibly through "Environmental Impacts", "Modern Infrastructure", "Sustainable Production", "Circular Economy", and "Degrowth", all of which are social impacts relevant to organisational activities that can promote social responsibility [24].

AM's ability to be deployed across society – homes, schools, universities, industry – and in varied environmental conditions demonstrates its potential to accommodate a wide-range of dynamic and distinct production constraints. It enables distributed manufacturing and is proposed as an alternative where '*small, flexible and scalable geographically distributed manufacturing units are capable of exhibiting the characteristics desired of modern operating systems*' implying a '*move away from long supply chains, economies of scale and centralisation tendencies towards a network paradigm*' [25]. Thus, having the potential to meet Driver 3 (Adapting to production constraints).

AM's capability continues to grow with the number of materials AM can process, speed of production and market having all doubled in the past 5 years [26]. Machines are now capable of printing circuitry and multiple materials enabling all manner of products – food, clothes, medicines – to be produced through a single manufacturing process.

Capabilities that are fundamental for facilitating manufacturing independence (Driver 4) in developing and small developed nations.

3.2 Agent-Based Manufacturing to Co-ordinate AM

Whilst AM represents the enabling technology[1], its diverse and distributed deployment across society – homes, education and industry – necessitates means for effective co-ordination. This has been identified with researchers modelling and simulating the potential of co-ordinated AM architectures and production optimisation processes. For example, [27] reviewed AM supply chains, which revealed the opportunity and interest from AM businesses for novel production system approaches that take advantage of the interoperability of machine code between AM machines, and ability to provide the same quality assurances if the same machines are being used.

Agent-based modelling of co-ordinated AM machines in a workshop setting reveals[2] considerable variance in the productivity and responsiveness of a system based on the API architecture (e.g., hierarchical, semi-heterarchical, heterarchical and anarchic communication) interacting with the platform and production logics (e.g., First-Come First-Serve, Largest Print First Serve) (Fig. 5) [21, 28]. This reveals that an agent-based AM production system is highly configurable and therefore, it is likely an optimal configuration exists to support the future demand scenarios that society will face.

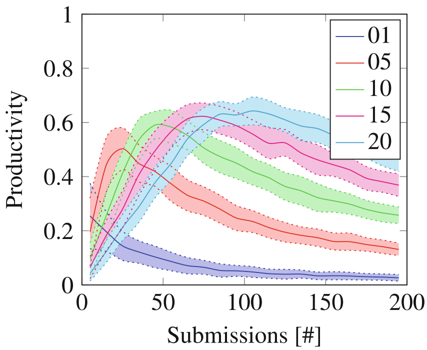

Fig. 5. Monte-Carlo simulation results of a user-led first-come-first-serve strategy with increasing production system size and demand [28].

In addition, the interoperability of the production code (e.g., G-Code) used on AM machines has also been exploited by [29] where they have shown that AM print beds can be optimally filled by splicing multiple distinct client jobs together. This results in a reduction of changeovers with the AM machine being able to manufacture for longer periods of time without interruption.

[1] It is also acknowledged that any manufacturing processes that feature the characteristics outlined in 3.1. could also be considered a candidate for meeting the drivers.

[2] Where each machine is its own agent governing what it shall/shall not produce.

3.3 Opportunity for Novel Brokering

We now have the manufacturing technology and the means by which to co-ordinate it but there also needs to be the means by which we broker jobs between clients and suppliers. The past decade has seen many innovations in the brokering of services between clients and suppliers [30, 31]. Examples include, Amazon, AirBnB, Uber and Deliveroo. Important to their success has been in how the data and information required of clients is submitted to a service, how suppliers can bid for jobs and offer services both through human and automated machine agent means, and how clients select the suppliers for their jobs. While novel brokering solutions have seen success in other sectors, this is an area that requires further exploration for production. And [27] has shown that the AM community is keen to explore novel brokering methods with organisations participating in human-led marketplace style production solutions where humans are able to bid/compete for jobs being submitted by potential clients (e.g., 3DHubs).

4 Discussion and Future Work

The paper has revealed four drivers for new production practice and a new production paradigm of brokered agent-based production to complement and, in some cases, supersede current practice. However, the paradigm is based on preliminary research and thus, further work in understanding the dynamics of such a system and the brokering protocols required is needed. The first area is characterisation and the need:

1. To characterise the drivers to develop product demand profiles that we can use in production systems research.

   The second area is technical and the need:

2. To develop new production system architectures for brokered production of highly distributed and diverse manufacturing capability.
3. To evaluate the emergent scaling behaviour of brokered architectures from communities to cities, regions and nations.
4. For real-world application of coordinated and brokered AM production to validate the theory and deliver real-world impact.

   The third area is management and the need:

5. To develop the business models and local/regional/government policy for economically viable brokered production.

   The fourth area is societal and the need:

6. To evaluate the thoughts of consumers and their feelings towards novel manufacturing practices and whether it would affect their purchasing habits.

5 Conclusion

Society is driving the need for production system change with weaknesses in our current production practice having been exposed by events such as COVID-19, trade disputes and BREXIT. While the drivers are known to exist, little work has been performed to synthesise the set of drivers to direct D&M production research.

Through thematic analysis, this paper has unpacked four societal drivers for production system change: meeting Big Demand; producing sustainably; managing highly dynamic and distinct constraints; and facilitating local, regional and national manufacturing independence. The paper then continues to identify a potential solution through a brokered agent-based production paradigm and is evidenced by literature. However, the paradigm is based preliminary research findings and more work is required to truly realise its potential. This has been noted through six areas that need to be addressed by the manufacturing community. The elicitation of the drivers and needs contributes to the discourse on meeting achieving sustainable and responsive manufacturing.

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References

1. Sarkis, J., Cohen, M.J., Dewick, P., Schröder, P.: A brave new world: lessons from the COVID-19 pandemic for transitioning to sustainable supply and production. Resour. Conserve. Recycl. **159**, 104894 (2020)
2. Anon: Coronavirus: UK sees almost no car manufacturing in April. https://www.bbc.co.uk/news/business-52838363
3. Comptroller. The supply of personal protective equipment (PPE) during the COVID-19 pandemic technical representative. National Audit Office (2020)
4. Alford, D., Sackett, P., Nelder, G.: Mass customisation—an automotive perspective. Int. J. Prod. Econ. **65**, 99–110 (2000). ISSN: 0925-5273
5. Piller, F.T., Müller, M.: A new marketing approach to mass customisation. Int. J. Comput. Integr. Manuf. **17**, 583–593 (2004)
6. Coronado, A.E., Lyons, A.C., Kehoe, D.F., Coleman, J.: Enabling mass customization: extending build-to-order concepts to supply chains. Prod. Plan. Control **15**, 398–411 (2004). https://doi.org/10.1080/0953728042000238809
7. Anon: EPSRC strategic priorities. https://epsrc.ukri.org/research/ourportfolio/themes/manufacturingthefuture/strategy/priorities/
8. O'Brien, C.: Sustainable production–a new paradigm for a new millennium. Int. J. Prod. Econ. **60**, 1–7 (1999)
9. Sumner, A., Mallett, R.: The Future of Foreign Aid: Development Cooperation and the New Geography of Global Poverty. Springer, London (2012). https://doi.org/10.1057/9781137298881
10. George, S.: How the Other Half Dies. Rowman & Littlefield Publishers (1989)
11. Hauschild, M., Jeswiet, J., Alting, L.: From life cycle assessment to sustainable production: status and perspectives. CIRP Ann. **54**, 1–21 (2005). https://www.sciencedirect.com/science/article/pii/S0007850607600171. ISSN: 0007-8506

12. Krajnc, D., Glavič, P.: Indicators of sustainable production. Clean Technol. Environ. Policy **5**, 279–288 (2003)
13. de Ron, A.J.: Sustainable production: the ultimate result of a continuous improvement. Int. J. Prod. Econ. **56–57**, 99–110 (1998). Production Economics: The Link Between Technology and Management. ISSN: 0925-5273
14. Anon: Trade set to plunge as CCOVID-19 pandemic upends global economy. https://www.wto.org/english/news_e/pres20_e/pr855_e.htm
15. Richter, F.: These are the top-10 manufacturing countries in the world. https://www.weforum.org/agenda/2020/02/countries-manufacturing-trade-exports-economics/
16. Moradlou, H., Backhouse, C., Ranganathan, R.: Responsiveness, the primary reason behind re-shoring manufacturing activities to the UK. Int. J. Phys. Distrib. Logist. Manage. **47**(2/3), 222–236 (2017)
17. Bailey, D., De Propris, L.: Manufacturing reshoring and its limits: the UK automotive case. Camb. J. Reg. Econ. Soc. **7**, 379–395 (2014)
18. EU/AZ Covid-19 vaccine row: what's the exit strategy? https://www.pharmaceutical-technology.com/features/eu-az-vaccine-row-covid-19/
19. Birtchnell, T., Hoyle, W.: 3D Printing For Development in the Global South: the 3D4D Challenge. Springer, London (2014). https://doi.org/10.1057/9781137365668_2
20. George, S.: How the Other Half Dies: The Real Reason for world Hunger (1986)
21. Gopsill, J., Goudswaard, M., Ma, A., Nassehi, A., Hicks, B.: Responding to rapidly changing product demand in light of COVID-19 through co-ordinated additive manufacturing production systems. In: Proceedings of the 9th Manufacturing Engineering Society International Conference (MESIC 2021) (2021, in press)
22. Holmström, J., Liotta, G., Chaudhuri, A.: Sustainability outcomes through direct digital manufacturing-based operational practices: a design theory approach. J. Cleaner Prod. **167**, 951–961 (2018). ISSN: 09596526
23. Gebler, M., Schoot Uiterkamp, A.J.M., Visser, C.: A global sustainability perspective on 3D printing technologies. Energy Policy **74**, 158–167 (2014). http://dx.doi.org/10.1016/j.enpol.2014.08.033. ISSN: 03014215
24. Naghshineh, B., Ribeiro, A., Jacinto, C., Carvalho, H.: Social impacts of additive manufacturing: a stakeholder-driven framework. Technol. Forecast. Soc. Change **164**, 120368 (2021). ISSN: 0040-1625
25. Srai, J.S., et al.: Distributed manufacturing: scope, challenges and opportunities. Int. J. Prod. Res. **54**, 6917–6935 (2016). ISSN: 1366588X
26. Lee, P.: 3D printing reaches the "plateau of productivity". https://www.deloitte.co.uk/tmtpredictions/predictions/3d-printing/
27. Johns, J.: Insights on additive manufacturing: value, volume and reshoring. ISSUU (2020). https://issuu.com/home/published/additive_manufacturing_industry_repo
28. Gopsill, J.A., Hicks, B.J.: Investigating the effect of scale and scheduling strategies on the productivity of 3D managed print services. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. **232**(10), 1753–1766 (2017)
29. Gopsill, J.A., Hicks, B.J.: The issues & challenges of 3D managed print services: towards a support tool for 3D MPSs. In: Proceedings of the International Conference on Sustainable Design and Manufacturing (2015)
30. Meijerink, J., Keegan, A.: Conceptualizing human resource management in the gig economy. J. Manag. Psychol. **34**, 214–232 (2019)
31. Williams, T.A., Shepherd, D.A.: To the rescue!? Brokering a rapid, scaled and customized compassionate response to suffering after disaster. J. Manage. Stud. **55**, 910–942 (2018)

Corporate Strategy Based Quantitative Assessment of Sustainability Indicators at the Example of a Laser Powder Bed Fusion Process

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Abstract. The definition of the sustainability of a product or a process depends on certain consideration. Frameworks for a methodological evaluation of environmental sustainability are proposed in ISO 14040/44 though a standardized assessment based on fixed parameters and standards is not suitable for every application. Here, an approach to define sustainability based on individually formulated corporate strategies using the example of the “cradle-to-grave” assessment using Laser Powder Bed Fusion (LPBF) as an additive manufacturing process is presented. By means of this approach, components of corporate strategies are identified and analyzed regarding existing conflicting goals and correlated with previously defined sustainability potentials. The result of this correlation is strategy-specific influencing factors, indicators and quantifiable variables that relate to the process chain of the LPBF method under investigation. A method is presented which, based on the correlations determined, enables to quantitatively assess the sustainability of the product during its life cycle. The application of this method is shown and verified at the example of two literature-based corporate strategies. Finally, the challenges for future developments of sustainability-oriented quantification options are discussed on the basis of the results.

Keywords: Sustainability assessment · Corporate strategy · Laser Powder Bed Fusion

1 Introduction

In the process of the current omnipresent sustainability debate, politics as well as science and economy are taking a critical look at the development of the interplay between humanity, the environment and the available resources [1]. This leads to the question of how long-term entrepreneurial growth can be generated without damaging the pillars of sustainability. In the scope of this paper, a methodical procedure is to be developed in order to be able to identify influencing factors for a sustainability assessment of the LPBF-process on the basis of a superordinate, individually composed corporate strategy.

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Using a literature-based identification of company-specific strategy components and the determination of positive and negative strategy-dependent goal conflicts, sustainability potentials are combined with the process chain of the LPBF method on the basis of the frame work of Ehlers et al. (2020) [2]. As a consequence, process-specific influencing factors as well as indicators and quantifiable variables can be identified as a result of the approach result. The method is then verified on two differently oriented company strategies and the results are discussed in conclusion. The research results are available as raw data in Wurst (2021) and will be published following this paper [3].

2 Theoretical Approach

2.1 Corporate Strategies

Regardless of the nature of formulated goals and actions require a strategy as a planned behaviour in order to be able to achieve these goals in interaction with the environment [4]. Thus, in addition to goals and visions, a strategy includes both necessary actions and a defined time horizon [5]. A strategy function as a guidance in dealing with complex situations [6]. In this context, a corporate strategy is a possibility for goal-oriented and long-term planning without ignoring the changing environment [7].

In addition to planning as a "path-goal" description, a corporate strategy comprises four further fundamental aspects for building up and maintaining success potentials. In the form of the "5 P's", Mintzberg (1987) summarises the contents of a corporate strategy as "Plan", "Ploy", "Pattern", "Position" and "Perspective" [8–10]. In the course of the "Ploy", elaborated tactics are placed in a target context and combined with decision patterns and regularly used types of action in the "Pattern" phase. Beyond the boundaries of the company, the "Position" and "Perspective" phases serve both the external positioning in competition and the perception by the environment [8–10].

Based on these aspects of a strategy, Ant (2018) presented a "10-phase" model for developing a corporate strategy. Divided into phases - starting with the "mission statement" and ending with the "evaluation of the overall approach" - it is possible to develop a strategy from the initial situation to the archievement of strategic goals [8]. In this paper, the focus is on the fifth and sixth phase of the model the fundamental question of the orientation of a corporate strategy is answered in these phases. Based on a multidimensional consideration of the problem in the course of the elaboration of scenarios, versatile approaches to solutions can be developed as an innovative basis for new strategic approaches [8]. Building on these scenarios, the vision of the company can be formulated as an orientation for all future developments [7]. In this sixth phase, the directions of the company are sustainably defined with the aim of realising long-term economic growth. By combining different competitive strategies that are approximately congruent in their goal orientation, there is the possibility of forming a long-term competitive advantage [8]. This competitive advantage is based on the assumption that all strategic considerations in the company are unique and cannot be imitated by the competition [8].

Identification the Components of a Corporate Strategy. As this paper focuses on the sustainability of production and manufacturing processes, it is first necessary to identify the components of corporate strategies that are directly related to value creation in the production context.

Assuming that a corporate strategy significantly supports the pursuit of corporate goals, each corporate strategy must be seen as an individual combination of different components [5]. The identification of requirements involves according to Mintzberg (1987) three questions [10]:

- “On what principle are the results of the company’s decisions based?”
- “What goals is the company pursuing?”
- “How does the company see itself in the market/competition?”

To identify a component of a corporate strategy, one or more of these questions must be answered. Based on a literature research, 23 different components could be identified, each of which is to be understood as a collective term that summarises the strategy scenarios described in the literature [3]. The focus of the literature examined lies in the areas of strategic management and strategy development. In addition, publications in the context of lean management and corporate social responsibility allow statements regarding the effects on related corporate strategies.

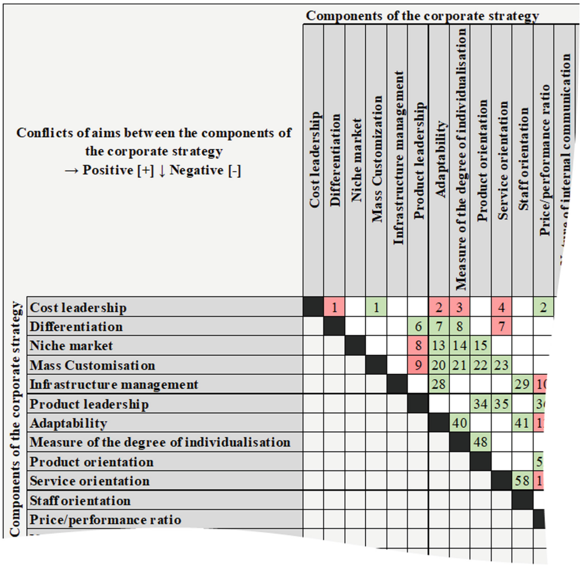

Fig. 1. Detail of the matrix of conflicting goals between the components of the corporate strategy [3].

For the example of the component of “product orientation”, the corporate strategy is based on the assumption that all measures of the company are oriented on both the company and the life cycle of the products [8, 11]. Thus, increasing sustainability across the different phases of the product life cycle is a linked corporate objective [8, 11]. The latter - the form of the competitive advantage - also provides an answer to the questions of what position the company occupies in the market and how the goal of building a sustainable competitive advantage through the product is to be realised.

Identifying the Conflicting Goals of the Components of a Corporate Strategy. Moreover, with the aim of capturing sustainability as holistically as possible, the question arises as to what extent the various components of the corporate strategy exhibit synergy effects among each other.

On the one hand, positive synergy effects should be utilised through mutually reinforcing interrelationships and, on the other hand, it should be possible to exclude contradictory strategy components.

The 93 identified positive and negative conflicting aims are partially depicted in Fig. 1 in form of a matrix and are based on the interrelationships described in the literature, starting with the analysis of exemplary companies or entire sectors. The various strategy components are plotted on both axes and then correlated with each other. The identified correlations were made up of both basic the results of case studies with a practical orientation and economic correlations, such as the possibility of customer-specific individualisation through the design of products (22) [12].

For the example of "differentiation", a positive conflict of objectives can be identified with the strategy component of "increasing innovative capacity". This positive link is based on the fact that innovative companies pursue the goal of developing a competitive advantage that cannot be imitated or substituted [13].

2.2 Potentials for Sustainability

Identification of Sustainability Potentials for the LPBF Process. The identification of sustainability potentials is one way to capture the sustainability definition within concrete production processes or product life cycles [2]. These potentials provide the connection between the individual corporate strategy and the resulting definition of multidimensional sustainability with the manufacturing process under investigation. Following the framework of Ehlers et al. (2020), there are also positive and negative relations between these potentials [2].

Each sustainability potential can be assigned to one or more sustainability dimensions depending on the impact of the potential. Since the focus of this paper is a generative manufacturing process, the relevant sustainability potentials are primarily located in the economic and the ecological dimension [2, 14, 15].

Identifying the Factors Influencing Sustainability Using the Example of the Process. In order to be able to identify influencing factors of sustainability using a concrete example, influencing factors are first defined according to Weltring (2015) as possibilities of "recording determinants that influence a target value as objectively as possible" [16]. Specifically related to sustainability, the following questions can be formulated:

- "What factors influence [the sustainability of the analysed manufacturing process] and in what way?"
- "What is the cause and reason for this influence?"

Based on these questions, the process chain of the LPBF process is examined as a collection of the processes directly affecting the target value to identify influencing factors. According to Lachmayer et al. (2016), this can be divided into four process sections and associated process steps (cf. Fig. 2 according to [17]).

Through a comprehensive literature research based on publications that deal with the definition and evaluation of sustainability and those whose contents focus on the concepts and implementation of additive manufacturing processes, a total of 18 different factors influencing sustainability for the LPBF process chain can be identified. Since the "preceding processes" of production are material-dependent and not individually adaptable, this process section as well as the associated process steps cannot be adapted to the orientation of the company [3, 17, 18].

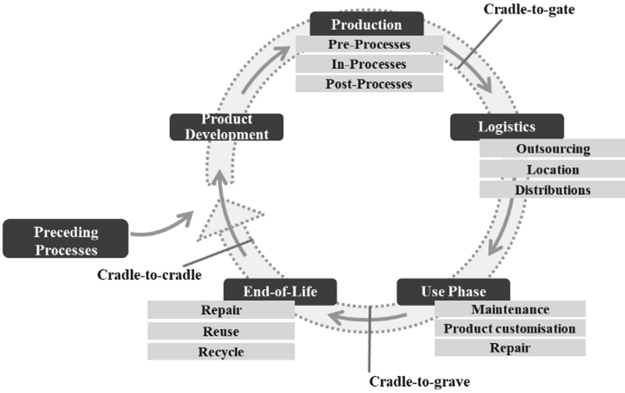

Fig. 2. Process chain of the LPBF method according to Lachmayer et al. (2016) [17]

In the product development phase the method for identifying the influencing factors can be explained. First of all, it is necessary to answer the initial question of what factors has a significant influence on which of the three sustainability dimensions in this process step. Since the focus is on exploiting the targeted potentials, both the design of the production processes and the material to be used must be adapted. As a result three influencing factors in the form of "process design", "material selection" and "exploitation of potentials" emerge as relevant. The second question to be answered relates to the causes and reasons for this influence on the sustainability of the LPBF process. In this context, indicators for each of the identified influencing factors were determined on the basis of a literature review. Each indicator serves to capture values that positively or negatively impact the influencing factor. For the example of "material selection", the proportion of toxic substances that are processed during the production of the component offers a possibility for a cross-process comparison. In addition, the relative proportion of primary resources used provides information on the acceptance of the process in relation to the use of recycled secondary resources.

Classification of the Influencing Factors in the Context of Sustainability Potentials Using the Example of the Process Chain of the LPBF process. In determining the sustainability potential of an influencing factor or related indicator, a cause-and-effect relationship must exist between them. Regardless of the characteristic, in the form of a positive or negative cause-effect relationship, there is a direct dependency and thus also an influence on sustainability. Moreover, a potential can be assigned not to just one indicator, but to a large number of different indicators that can extend over the entire product life cycle. Based on this assumption, it is possible to capture as holistic a picture of sustainability as possible with a small number of different potentials. The linked data of the assessable factors serve - analogous to classic key performance indicators - to monitor the current company performance [5]. In context of this paper, "sustainable corporate performance" is the measure of congruence between the corporate strategy and the company-specific sustainability strategy.

As a result of this assignment, a varying number of sustainability potentials outcomes for the different influencing factors and indicators. For a better understanding of the assignments made, the four indicators "operating materials", "auxiliary materials", "process and cooling water" and "length of the value chain" can be identified for the example of the influencing factor "process design", which can be assigned to both cross-influencing factor and indicator-specific potentials.

Thus, the "reduction of waste" and the "increase of process efficiency" result as characteristic sustainability potentials for the considered influencing factor of "process design". Since in the process section of production the degree of waste correlates directly with the efficiency of the processes, these are linked, among other things, to the consumption of operating materials [19].

Impact and dependency matrix between the components of the individual corporate strategy and the identified potentials of sustainability	Collection of potentials related to a targeted increase in sustainability									
Components of the corporate strategy	Reduction of CO2 emissions	Reduction in the use of resources	Development of alternatives to conventional manufacturing	Increasing functional integration	Reducing energy consumption	Reducing waste	Reducing wastage	Expanding hybrid production	Increasing recyclability	Improving the use of digitalisation
Cost leadership			O		O		X			
Differentiation	O		X	X				X	X	X
Niche market	O		X	X				X	X	X
Mass Customisation					X	X	X	X		X
Infrastructure management	X	X	O		X	X	X	O	X	X
Product leadership				X					X	
Adaptability		O	X	X	O		O	X	X	X
Measure of the degree of individualisation			O	X				X	O	X
Product orientation				X					X	
Service orientation				X		O	O	O	X	O
Staff orientation			X			X	X	O		X
Price/performance ratio				X	X	O	O		X	O
Nature of internal communication										
Customer-oriented										

Fig. 3. Detail of the created impact and dependency matrix between 23 components of corporate strategies and 53 potentials of sustainability

The higher the relative ratio of input to output resources, the higher the process efficiency. There is thus a positive correlation between the indicator and the potential.

The potential "reduction of process steps" for the indicator "length of the value chain" is used as an example of an indicator-specific potential allocation. The length of the value chain decreases as well as the number of individual process steps as example for a positive correlation [3, 20].

Linking the Identified Influencing Factors with Components of the Corporate Strategy. To establish a link between the components of the corporate strategy, the production process under consideration and sustainability, the following combinatorics can be applied. The desired result of this linkage is an individually structured collection of relevant assessable variables for the LPBF process under investigation with indicators to be checked.

The direct (X) and indirect (O) links are combined in an effect and dependency matrix, which is shown as an example in Fig. 3. For the example of the strategy component of the "price/performance ratio", there is both a direct link with "energy consumption" during production and an indirect link with the "reduction of waste" due to inefficient processes and resulting increased production-specific costs in contrast to lean and thus sustainable production.

3 Literature-Based Case Study

In order to verify the method presented in this paper for linking corporate strategy with sustainability potentials, the assumptions made in this section are applied to two different literature-based corporate strategies as impulse generator, which is responsible for the composition of relevant assessable variables. In this context a corporate strategy from the field of the LPBF process and a sustainability-oriented corporate strategy are considered. Based on the method's results using two different corporate strategies, a conclusion is to be made regarding the reliability of the method's use.

The corporate strategy presented by Dispan et al. (2014) is based on current developments in the context of megatrends such as globalisation, demographic change and the advancing energy transition, the five strategy components listed in Table 1 serve as the reference for the sustainability strategy [21]. Assuming that digitalisation is a significant innovation driver for the formation of new business models and corporate strategies, the derived strategy focuses on internal corporate aspects [22].

In contrast to this sustainability orientation, the corporate strategy according to Echterhoff et al. (2016), with the elaboration of a B2B platform for additive manufacturing, is based on a future-oriented corporate strategy that focuses not only on traditional resource but also on human resource use [23]. Compared to the sustainable strategy components according to Dispan et al. (2014), Echterhoff et al. (2016) pursues the goal of building both the highest possible customer loyalty and market position [23].

3.1 Application of the Previously Described Method

Identify Sustainability Potentials of the Corporate Strategies Under Consideration. In identifying sustainability potentials for the two exemplary corporate strategies on the

Table 1. Identified components of corporate strategies according to Echterhoff et al. (2016) and Dispan et al. (2014)

Echterhoff et al. (2016)	p.	Dispan et al. (2014)	p.
Mass customization	13	Adaptability	64f
Product leadership	13	Staff orientation	63/65
Measure of the degree of individualisation	13	Nature of internal communication	63
Service orientation	13	Focus on rapid product development	63
Customer-oriented	13	Green corporate orientation	66

basis of the various identified strategy components, a preliminary analysis is required. Figure 4 shows the process of the method including the outcomes determined. In relation to the conflicting goals identified in advance, this results in positive and negative correlations between the strategy components for both corporate strategies, on the basis of which a statement can be made regarding the compatibility of these components. As an example for the corporate strategy according to Echterhoff et al. (2016), there is a positive conflict of objectives between "personnel orientation" and a "'green' corporate orientation", since according to Stibbe (2017) a commitment of the employees concerned is necessary in order to be able to successfully implement new aspects within a company [24].

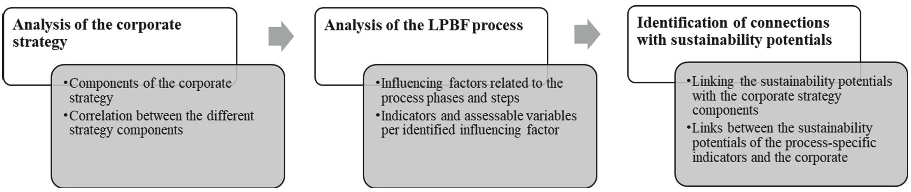

Fig. 4. Illustration of the applied method and identified factors

With the help of the developed impact and dependency matrix, a strategy-specific selection of relevant sustainability potentials can be created for the strategy components. For the concrete example of the strategies according to Echterhoff et al. (2016) and Dispan et al. (2014), a different collection of sustainability potentials results analogous to the varying strategy components. As a result of the classification of the strategy components in the effect and dependency matrix in which the sustainability potentials are classified with the components of the corporate strategy [3].

As the only sustainability potential of "improved handling of digitalisation" can be identified as an interface between the two corporate strategies. This can be explained by the increasing necessity of internal company networking and the megatrend of intelligent manufacturing [21]. According to Mohr (2020) advancing digitalisation allows for new innovation opportunities that go beyond the limits of pure production purposes and forms the basis of all future potential and must be incorporated into a future-oriented corporate strategy [22].

Following the framework according to Ehlers et al. (2020), the sustainability potentials are related to each other and are upstream and downstream of each other [2]. Through these lever-potential relationships, a holistic picture can be created beyond the boundaries of the three dimensions, whereby a classification in the overarching sustainability context can take place.

This collection of related sustainability potentials forms the intersection between the corporate strategies under consideration and the process chains of the LPBF process under investigation.

Deriving the Influencing Variables Based on the Sustainability Potentials. For the example in the corporate strategy according to Echterhoff et al. (2016), two primary and 15 secondary indicators can be determined, and analogously for the sustainability strategy according to Dispan et al. (2014), 17 secondary indicators can be determined [3, 21, 23]. Due to the varying composition of these relevant indicators, statements can be derived regarding the focus within the process chain, as the indicators show strategy-specific deviations. The focus of the sustainability strategy is on the one hand on the process steps preceding the product development and on the other hand on the pre- and post-processes of production. In comparison to the strategy of additive manufacturing, the focus lies in the area of product development, the in- and post-processes of production and the phases of the end-of-life.

4 Conclusion and Outlook

The entire paper is based on the assumption that the individual design of the corporate strategy has a direct influence on the resulting sustainability of the process. To demonstrate this it can be observed that the various sustainability potentials and the influencing factors derived from them in the process chain of the two corporate strategies examined differ from each other. This divergence is thus the first consequence of a differentiation in corporate strategy. When the associated assessable factors are complemented with real values, further differences emerge within the resulting assessment process.

Another way of differentiating the results is to look at the primary and secondary influencing factors separately. This strategy-specific differentiation allows a statement regarding the compatibility of the primary identified potentials and dependent secondary levers. The iterative application of the method with constant assessable variables resulting from the underlying corporate strategy offers a possibility to identify internal changes in the area of sustainability. Depending on the characteristics of the period under consideration, a tendency can be determined as to whether and to what extent the available sustainability potentials can be exploited.

The developed method as well as the presented connections between sustainability potentials, components of the corporate strategy and the influence on the LPBF process generate strategy-specific results in the form of assessable variables. It is a way of linking purely economic strategic management with the actual product life cycle. The validity of this method must be verified with the help of a data collection of the identified evaluation variables on the example of a demonstrator component. Important for the application of this method as well as a potential comparison of sustainability is the collection of data over the entire life cycle of the product in order to be able to determine a picture of the procedures, processes and products that is as holistic as possible.

In order to minimise the risk of inferior data quality due to a lack of data availability, Life Cycle Assessment databases, such as "ecoinvent", as well as holistic life cycle assessment software can be used to support the process.

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References

1. Schmid, E., Pröll, T. (eds.): Umwelt- und Bioressourcenmanagement für eine nachhaltige Zukunftsgestaltung, 1st edn. Springer, Heidelberg (2020). https://doi.org/10.1007/978-3-662-60435-9
2. Ehlers, T., Wurst, J., Lachmayer, R.: Bewertung der ökologischen und ökonomischen Nachhaltigkeit in der Additiven Fertigung. In: Lachmayer, R., Rettschlag, K., Kaierle, S. (eds.) Konstruktion für die Additive Fertigung 2019, pp. 177–199. Springer, Heidelberg (2020). https://doi.org/10.1007/978-3-662-61149-4_12
3. Wurst, J.: Linking the corporate strategy with sustainability potentials and influencing factors of the laser powder bed fusion process: additional tables for understanding the results (2021). https://seafile.cloud.uni-hannover.de/d/cca1444db9964e368d78/. Accessed 01 Apr 2021
4. Bamberger, I., Wrona, T.: Konzeptionen der strategischen Unternehmensberatung. In: Bamberger, I., Wrona, T. (eds.) Strategische Unternehmensberatung: Konzeptionen - Prozesse - Methoden, 6., aktual. und erw. Aufl, pp. 1–43. Springer, Wiesbaden (2012). https://doi.org/10.1007/978-3-8349-3772-8_1
5. Waurick, T.: Prozessreorganisation mit Lean Six Sigma. Springer, Wiesbaden (2014). https://doi.org/10.1007/978-3-658-07754-9
6. Scherr, M., Berg, A., König, B., et al.: Einsatz von Instrumenten der Strategieentwicklung in der Beratung. In: Bamberger, I., Wrona, T. (eds.) Strategische Unternehmensberatung: Konzeptionen - Prozesse - Methoden, 6., aktual. und erw. Aufl., pp. 77–104. Springer, Wiesbaden (2012). https://doi.org/10.1007/978-3-8349-3772-8_3
7. Ant, M.: Effizientes Strategisches Management. Springer, Wiesbaden (2018). https://doi.org/10.1007/978-3-658-21827-0
8. Harburger, W.: Die Logik der Strategieentwicklung. Springer, Wiesbaden (2019). https://doi.org/10.1007/978-3-658-26628-8
9. WenJun, J.: Reinterpretation of the strategic concept based on Mintzberg's strategic 5p model. Front. Soc. Sci. Technol. **1**(6), 30–33 (2020). https://doi.org/10.25236/FSST.2019.010606
10. Mintzberg, H.: The strategy concept I: five P's for strategy. Calif. Manage. Rev. **30**(1), 11–24 (1987)
11. Wunder, T. (ed.): CSR und Strategisches Management: Wie man mit Nachhaltigkeit langfristig im Wettbewerb gewinnt. Management-Reihe Corporate Social Responsibility. Springer, Heidelberg (2016). https://doi.org/10.1007/978-3-662-49457-8
12. Kumke, M.: Methodisches Konstruieren von additiv gefertigten Bauteilen. Springer, Wiesbaden (2018). https://doi.org/10.1007/978-3-658-22209-3

13. Schneider, K., Bullinger, H.-J., Scheer, A.-W.: Service Engineering: Entwicklung Und Gestaltung Innovativer Dienstleistungen. Springer, Dordrecht (2005). https://doi.org/10.1007/978-3-662-09871-4_1
14. Caviezel, C., Grünwald, R., Ehrenberg-Silies, S., et al.: Additive Fertigungsverfahren (3-D-Druck): Innovationsanalyse. TAB Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (2017)
15. Gebhardt, A.: Understanding Additive Manufacturing: Rapid Prototyping, Rapid Tooling, Rapid Manufacturing. Hanser, Munich (2012)
16. Weltring, R., Crezelius, S., Hallbauer, M.: Produktivitzätsmanagement für industrielle Dientsleistungen stärken: PROMIDIS Handlungsleitfaden - Dimension der Produktivitätssteigerung (2015)
17. Lachmayer, R., Lippert, R.B., Fahlbusch, T. (eds.): 3D-Druck beleuchtet. Springer, Heidelberg (2016). https://doi.org/10.1007/978-3-662-49056-3
18. Lachmayer, R., Lippert, R.B.: Lohnt sich die additive fertigung? In: Lachmayer, R., Lippert, R.B. (eds.) Entwicklungsmethodik für die Additive Fertigung, 1st ed. pp. 141–159. Springer, Heidelberg (2020). https://doi.org/10.1007/978-3-662-59789-7_8
19. van Elsen, M.: Complexity of selective laser melting. A new optimisation approach. Dissertation, Katholieke Universiteit Leuven (2007)
20. Biedermann, H. (ed.): Umweltverträgliche Produktion und nachhaltiger Erfolg: Chancen, Benchmarks & Entwicklungslinien, 1. Aufl. Sustainability Management for Industries, vol. 4. Hampp, München (2011)
21. Dispan, J., Pfäfflin, H.: Nachhaltige Wertschöpfungsstrategie: Unternehmensstrategie im Kontext von Industriepolitik und Megatrends. Edition/Hans-Böckler-Stiftung, vol. 283. Hans-Böckler-Stiftung, Düsseldorf (2014)
22. Mohr, T.: Der Digital Navigator: Ein Modell für digitale Transformation. Springer Fachmedien Wiesbaden, Wiesbaden (2020). https://doi.org/10.1007/978-3-658-29704-6
23. Echterhoff, B., Gausemeier, J., Koldewey, C., et al.: Geschäftsmodelle für die Industrie 4.0. In: Echterhoff, B., Gausemeier, J., Koldewey, C., et al. (eds.) Geschäftsmodelle für die Industrie 4.0 // Digital vernetzt. Transformation der Wertschöpfung: Szenarien, Optionen und Erfolgsmodelle für smarte Geschäftsmodelle, Produkte und Services, pp. 35–56. Hanser, München (2017)
24. Stibbe, R.: Globales Life-Cycle-Controlling. Springer, Wiesbaden (2017). https://doi.org/10.1007/978-3-658-15660-2

Pathway for Designing with New DIY, Circular and Biobased Materials: Insights from Three Case Studies

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Abstract. In recent years, evidence shows the depleting consequences of bad material application on our planet. This drove research to designing new substitutive and less-polluting materials. Materials derived from biomass, known as biobased materials, hold much potential as is shown in previous research. In addition, research efforts are also being made to help industrial designers work with these new materials. However, each of the supporting methodologies developed today focuses only on one piece of the bigger picture. This article examines three case studies of designers working with DIY, circular and biobased materials and highlights the similarities and contradictions of their design processes. Designing applications for these new materials mostly enacts in large systems. This explains why research on designing with new DIY, circular and biobased materials is in need to use many different complementary methodologies in conjunction, whilst still maintaining a structured and organized overview on the research. Therefore, a possible pathway is suggested to potentially support the designer in structuring, organizing and overviewing the complex research and development process of designing with new biobased materials. Ultimately, this study suggests that future efforts should be devoted to applying and validating the supportive pathway and embracing its open-ended and indeterminate nature. Conclusively, this article additionally uncovers the interesting bridge between the domain of designing with new DIY, circular and biobased materials and the designer's behaviour within.

Keywords: Design for biobased materials · Design for DIY material · Design for circular materials

1 Introduction

Across the globe, environmental awareness is getting more and more its deserved attention. It is therefore crucial to explore acts that might contribute to the greater good of a positive human and planetary synergy. Herein, a sustainable development is the compilation of possible pathways that point towards sustainability as desired future objective, which has been recently represented by 17 global goals related to economy, society and

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environment. These three areas should be seen as integrated and nested in one another [1, 2]. Today, sustainability becomes a decision-guiding objective for several actors and can be seen as a system property, raising from the interaction of different actors, rules, technologies, infrastructures, etc. [3, 4].

In this context, it is not yet clear how sustainable societies should look like and therefore the role of design and technology becomes critical. On the one hand, design is seen as a discipline capable of potentially supporting others while tackling complex, unstable, uncertain, often conflictual – in other words wicked – realities [5, 6]. On the other hand, industrial design is considered responsible for facilitating the creation and diffusion of unsustainable production-consumption patterns – "there are professions more harmful than industrial design, but only a very few of them" [7, 8]. Therefore, the role of design should be taken into account in its dual responsibility of influenced/influencer of bigger socio-technical systems [9]. If design has the ability to imagine and even facilitate that-which-does-not-yet-exist, Design for Sustainability specifically focuses on outlining actions and tools that have the potential to bring the societal transitions in line with the SDGs [4, 10]. Design for Sustainability (D4S) is multi-faceted, multidimensional and takes place at several levels where the framing of the problem and the scope of the intervention vary greatly, respectively from technocentric to human-centric and from insular to systemic [11].

With this objective in mind, this research situates within the domain of industrial design engineering, as concerned with the emergent DIY, circular and biobased materials, and it is driven by the questions: How do industrial designers approach these emergent DIY, circular and biobased materials?

2 State of the Art

2.1 Materials and Design

Usually material development is performed by material engineers, however in this case designers step in the process of materials development. Herein lies the potential of the designers to deploy their wide, multidisciplinary skillset to research the material development through design. So did Karana et al. introduce the Material driven Design (MDD) Method. Accordingly, this MDD method facilitates designing for material experiences [12]. Another design methodology, called 'Open Ended Design' is concerned with the changing nature of products and systems relative to and influenced by their surroundings and the way this methodology embraces those characteristics. Open Ended design has in this respect been introduced in relation to designing with DIY, circular and biobased materials. Herein, Open Ended Design can be seen as an unfinished design, where the definition of its characteristics is left open and therefore, flexible [13]. Within the realm of DIY, circular and biobased materials, is the Growing Design methodology also often used for biomass-growing materials more specifically. In this sense, Growing Design is a relatively new design practice where designers collaborate with biology. It is an intersection between design, materials science, biology, arts and crafts. The designers are trying to forge organisms and their processes by creating specific conditions to guide their growth into a specific material or product [14]. Lastly, since design with DIY, circular and biobased materials mostly aim at closing waste system loops, they all operate within the Circular Economy paradigm [15].

Ultimately, DIY, circular and biobased materials research shows that all of the above is not particularly new, considering many research is already channeled towards the domain of designing with new biobased materials and the seemingly wicked nature of systems in which they behave, which may lead to a need to create pathways for designing with them in a more organized, structured and orderly manner [16, 17]. In order to do so, this article examines three case studies which dealt with DIY, circular and biobased materials.

2.2 DIY, Circular and Biobased Materials

DIY materials are bottom-up innovations, that allow quick experimentations with local resources. On top of that, DIY materials are not developed and designed with the purpose of replacing industrial materials, because this might be a long and expensive process. The field of DIY materials is even subdivided into five so-called kingdoms or categories, which are inspired by the first biological classifications [18].

Circular materials on the other hand, are materials that align to the concept of Circular Economy, they can be recycled, reused and/or have regenerative potentials [15].

Biobased materials are materials composed or derived in whole or in part of biological products issued from the biomass (including plant, animal, and marine or forestry materials) [19]. Elaborating on this definition from Vert et al., biobased materials are materials naturally grown, excluding the exhaustion of planetary scarce resources. It is this very aspect, together with many other benefits (i.e. biodegradability and other properties), that makes this research domain popular in recent years. Many efforts are hence channeled towards the creation of new, more performant biobased materials. Not to overlook the potential, new or alternative applications they can and will bring about. In this manner, many methodologies and frameworks have been introduced with the very purpose to support designers in their material application design process [12, 20–25]. It is important to note however, as all design tends to be flowing through a fuzzy front end procedure where many tools are deployed along the way, organization, structure and overview are key to developing new products or services, let alone designing with new DIY, circular and biobased materials. For this reason, this paper reviews and synthesizes three research case studies on application design with new DIY, circular and biobased materials. The objective of this research is to create insights on the similarities and dissimilarities of the design process of the three discussed case studies. Eventually a possible pathway is suggested to support design with these new DIY, circular and biobased materials in a more organized, structured and orderly manner.

3 Methodology

3.1 Research Through Design

In this work, *case study research* and, more generally *research through design*, are the overarching applied research methods. A major advantage of this approach, here qualitatively addressed, is its capacity to report on real-life contexts, where the design object and process becomes the center of our study. Specifically, the work of three design students, challenged to explore and design applications for new DIY, circular and biobased materials, have been observed and analyzed. Each design case studies had been documented by the students themselves in form of an unpublished extended abstract, where the design process is described in detail. For the here presented study, these extended abstracts are thoroughly read in order to achieve - case by case - a short list of insights on (1) the research question posed by the students ([a] application, [b] impact, [c] implementation), (2) the applied methodologies to find new application for the new materials and (3) the order of methodology deployment. It has been proceeded comparing the three cases seeking for similarities and dissimilarities regarding the three aforementioned points.

3.2 Case Studies Selection

All three cases derive from the curriculum of Industrial Design Engineering Technology of Ghent University, in Belgium. They have been developed in 2019 as master thesis projects. The three theses have been selected as case studies for this work because of their clear focus and engagement with the topic of DIY, circular and biobased materials. They each focused on developing and finding applications for a different material, with the commonality that all materials were not yet industrial nor readily available, therefore characterized by high uncertainty on their properties and possible applications – in other words ‘the materials have no identity yet’.

3.3 Case Studies Description

The three students’ design projects, analyzed as case studies in this paper were conducted in parallel over a course of one year. Each one of them focuses on a different DIY, circular and biobased material, namely: (1) a starch-based material developed from fruit- and vegetable waste, (2) a natural blueberry-based dye and (3) a naturally grown mycelium-based material in a biobased fibrous substrate. Also the goals of the theses were slightly different. The first attempts to develop and apply a new DIY and circular and biobased material from fruit- and vegetable waste, taking into account the complex system of waste salvaging to production, impact and implementation. The second focusses on designing suitable applications for a newly developed (and not yet industrialized) dye deriving from a very specific waste stream (blueberries) [26]. The third and last analyzed case, designs towards a specific application (a urn) for mycelium-based materials, where mycelium is the vegetative part of fungi [27].

4 Results

4.1 Case Study Research Questions

Before going any deeper on the three case themselves, it is considerable to note already the nuanced difference within the focus of the case studies’ research questions. First, the case focusing on food-waste-based materials asks "How can fruit and vegetable waste be valorized in a full-fledged product, that is more environmentally friendly than its alternatives?". Subsequently, the case focusing on natural-dye states "This paper questions applications for a natural blueberry-based dye". Ultimately the case focusing on mycelium-based materials wonders "How can a mycelium-based funeral urn be implemented into a business model?". Compiling those three research questions, this article differentiates between [a] the exploration around the application of the material only, [b] the extra effort to define the comparative impact of the material towards the traditional competitors and [c] the final efforts to draft commercial implementations of the identified applications.

4.2 Case Study Methodologies and Order of Deployment

Starting Up: Initial Unknowns and Uncertainties
Typical for new material application design, is to first get familiar with the new material at hand [20]. Cases 1 and 2 mentioned an experimental period in their design process, where the DIY materials are made by the design students in collaboration with field experts. Here, different material compositions are tried and documented. Desk research is performed in the field of the new materials. All of this until a basic understanding of the new material technology is established. This process is actually referred by one case study as 'exploratory design'. Exploratory design is the approach to immerse in a topic and all of its facets with the purpose to narrow down the options [20]. The remaining case 3, which did not mention such preliminary process, did however mention having prior knowledge of its material from a previous course.

Moving Forward: Following the Material-Driven Design Methodology
Having some basic knowledge on the new materials, the three designers took different methodological paths in their remaining design process. Furthermore, from this point the focus of their research question will drive their methodology deployment significantly. Although all three of the studies proceed with a similar design process, addressed in the next paragraph, they employ different, but equally valid methodologies with similar purposes. The key aforementioned process following on the exploratory design, is an overarching methodology as well, called the 'Material Driven Design (MDD)' Method [12]. Although this methodology is in its literature of origin specifically used for material design, all three research case studies applied and extended it to their material application design. Underlying are methodologies employed to characterize the materials, and subsequently design with their respective characteristics. So do case studies 1 and 2 express a process of testing their materials on their technical properties, i.e. physical, mechanical, thermal, optical properties, processing energy, durability, recycling, end-of-life, etc. Besides the technical properties, do all three case studies also express having investigated their materials' experiential characteristics. In this, previous studies have shown and strongly state that this part must not be overlooked, because it is as crucial as the technical characteristics in order to make a successful, pleasing and good appealing product [12, 21, 25]. Looking more deeply in the crucial step of characterizing the experiential properties of the materials, divergence emerges within the methodology deployment between the case studies. In the first study with fruit- and vegetable waste,

the experiential characteristics of the material had been determined through the combination of existing supporting theories and the conduction of user tests. So did the Meanings of Materials (MoM) model prove to be helpful - in case study 1 - in generating a map of all variables that contribute to the meaning attribution of a person to a material [21]. This model indicates that the sensorial and experiential material properties lack, but also the participant's mood and the material meanings. Eventually, Semantic Differential Scales prove to be an excellent tool to collect this data [28]. The second case however, goes more in depth with the application of the MDD methodology. This case study conducted user tests, followed by determining the design intentions by means of creating a material experience vision. Ultimately, material experience patterns are manifested to convert the experiential meanings towards a material application field. This second case study thus followed the MDD method more meticulously. The third and last case study did not refer in particular to the MDD method in this subsection, but did however follow a similar path. Kansei engineering was introduced to develop products that match consumers' preferences based on their kansei requirements [29]. The basic idea of kansei method is that; the customer's feelings and preferences are being explored already at the idea generation phase in the product development process, which then facilitate the project later with final intended product communication. Ultimately, using 'experience mapping' the design intentions for its material application structured the conceptual intentions of the designer [30].

Finalization: Identifying and Testing Possible Applications

Proceeding to the application design, each student applied a typical iterative and evolutionary approach to their whole design process. Creating an application field list that complies to all previous research outcomes, developing one application as an example, testing and validating its intentions and iterating again on the received feedback.

Two case studies pushed their research beyond the scope of application design. The mycelium-based case study (case 3) additionally researched the possibility to implement its material application in a business model. The food-waste case study (case 1) on the other hand went even further by also evaluating the materials' application impact on the environment using a comparative Life Cycle Assessment (LCA) approach, compared to substitutive products [23, 24]. Also, stated by one case study (case 1) of substantial importance as a methodology was 'Systems thinking', applied through a tool called 'System Archetypes' [31, 32]. Systems thinking supports designers in overviewing the interconnectedness in their design process and the environment in which their project behaves. This is an important tool in evaluating the impact of any design action and maintaining an overview.

4.3 Bridging the Respective Insights to the Designer's Behaviour

Having addressed the highly uncertain – even with no-identity – character of DIY, circular and biobased materials, which on top are not industrial, nor readily available; and besides that the key insights in form of commonalities and differences in design process approach; it is interesting to note and maybe even study the behaviour of designers within their design process. Questions around their behaviour arise, when wandering what designers drive to working with these new DIY, circular and biobased materials, since these materials must not be approached as the readily available, mass produced, commercial materials which everyone is familiar with in everyday products. On the contrary, these materials demand a whole different angle of attack in order to deploy them well within their scope of unique property compositions. Just as 3D printing technology found its way into industry, although with limitations to mass production; a way will need to be found for designers to pick up these DIY, circular and biobased materials through changes in their behaviour.

5 A Possible Pathway to Design with New DIY, Circular and Biobased Materials

The results of this study are the insights derived from the commonalities and differences within the design process of each of the three students. In addition to these resulting insights is a possible pathway suggested to support designers in their design process with DIY, circular and biobased materials. So does the differentiation between the three levels of focus already suggest a key important insight for the development of this supportive pathway. A second insight regards the similar deployment of a first stage, referred as the exploratory design, which is a crucial must for any new material application research. After exploratory design, is the need expressed to start designing from material knowledge. Meaning its characteristics, both technical and experiential. The data derived from this phase in the design process will help to design with meaning. A central methodology expressed to be of influence in all three case studies is the MDD method. Although MDD includes both technical and experiential properties, it is important to notice that MDD behaves in a wider context. This is also stated by Karana with the 'Meanings of Materials' model (MoM) [21]. This model maps all the variables that contribute to the meaning attribution of a person to a material. Considering more specifically the experiential characterization of the new biobased materials, many methodologies can be used to determine and validate them with customers, i.e. Kansei engineering, Experience Mapping, etc. The purpose of new biobased material application design is eventually to create a list of requirements for its field of application.

Along with the exploratory design- and MDD process, are highly iterative and evolutionary prototyping methodologies employed, i.e. growing design, and many more.

Once the field of application is established, research might take the leap to develop an application and examine its impact compared to a substitute product. A well proven methodology suggested here is the comparative Life Cycle Assessment (LCA), which is ISO standardized.

Finally, research can evaluate the economic viability of the developed product by completing a Flourishing Business Model Canvas (FBMC). The flourishing business model canvas differs from the default one, through its attempt to not only capture economic data, but also societal- and environmental data.

Of course, as mentioned before, applying Systems Thinking will support the designer in analyzing the impact of his actions, as well as overviewing the interconnectedness of his project and its environment/surroundings.

Lastly, as is showcased with these three case studies, no design process is exactly similar and many methodologies are at the designer's disposal, leaving him with a plethora of options and choice. Not losing organization, structure and overview is of key importance to any design process. Keeping track of all the gathered data, the available methodologies and the check points in the design process is therefore crucial, whereby a suggestive – yet supportive-pathway is not an unnecessary luxury for any designer. In addition, it can serve as a focal point to indicate what to include and/or exclude from the scope of new research in the area of designing with new DIY, circular and biobased materials. Ultimately, all the aforementioned insights from the commonalities and differences suggests this possible pathway (Fig. 1) for designing with new DIY, circular and biobased materials.

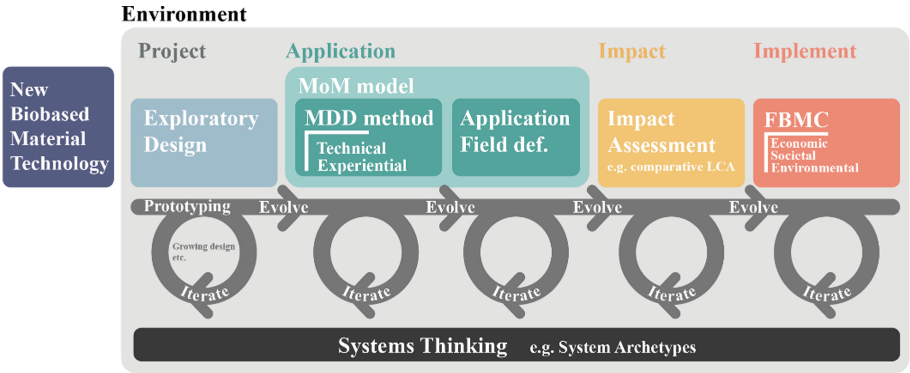

Fig. 1. Possible supportive pathway for designing with new DIY, circular and biobased materials

6 Discussion

Given the three research case studies over the course of one year and the insights derived from their design process, suggesting a possible supportive pathway, this work suffers from a number of limitations. First of all, the suggested supportive pathway is not empirically validated in new case studies. Secondly, this pathway is not definitive, nor trying to standardize the process of designing with new DIY, circular and biobased materials. Quite the contrary, this study encourages to embrace the open-ended character of this supportive pathway and shape it to your own needs in your design process. Thus if necessary, more complementary methodologies can and should be added in the future. What this pathway does however mean to bring about, is a critical thought on how to organize, structure and overview your design process and what aspects you could research on. This critical thinking about your process is essential in this field, as designing with DIY, circular and biobased materials has a broad context to work in. Furthermore, future validation will have to proof the purpose of the insights from this study and the suggested supportive pathway. In short, this open-ended possible pathway is purely directive and has, apart from the three case studies, not been empirically validated. Therefore, this reviewing study suggests future work to apply this open-ended pathway in new case studies within the field of designing with new DIY, circular and biobased materials, reflect on them and alter them to their needs. In addition, does this article articulate the interesting bridge to research the designer's behaviour in working with these new DIY, circular and biobased materials.

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References

1. UN (2015). https://sdgs.un.org/goals
2. Giddings, B., Hopwood, B., O'Brien, G.: Environment, economy and society: fitting them together into sustainable development. Sustain. Dev. **10**, 187–196 (2002). https://doi.org/10.1002/sd.199
3. Saviano, M., Barile, S., Farioli, F., Orecchini, F.: Strengthening the science–policy–industry interface for progressing toward sustainability: a systems thinking view. Sustain. Sci. **14**, 1549–1564 (2019). https://doi.org/10.1007/s11625-019-00668-x
4. Ceschin, F.: How the design of socio-technical experiments can enable radical changes for sustainability. Int. J. Des. **8**, 1–21 (2014)
5. Cross, N.: Designerly ways of knowing: design discipline versus design science. Des. Issues **17**, 49–55 (2001). https://doi.org/10.1162/074793601750357196
6. Rittel, H.: The state of the art in design methods. Des. Res. Methods **7**, 143–147 (1973)
7. Papanek, V., Hennessey, J.: Nomadic Furniture: How to Build and Where to Buy Lightweight Furniture That Folds, Collapses, Stacks, Knocks-Down, Inflates or Can be Thrown Away and Re-Cycled. Pantheon Books, New York (1973)
8. Schön, D.A.: The Reflective Practitioner: How Professionals Think in Action. Basic Books, New York (1983)
9. Giddings, B., Hopwood, B., Mellor, M., O'Brien, G.: Back to the City: A Route to Urban Sustainability. Architectural Press, Oxford (2005)
10. Nelson, H.G., Stolterman, E.: The Design Way: Intentional Change in an Unpredictable World. MIT Press, Cambridge (2012)
11. Ceschin, F., Gaziulusoy, I.: Evolution of design for sustainability: from product design to design for system innovations and transitions. Des. Stud. **47**, 118–163 (2016). https://doi.org/10.1016/j.destud.2016.09.002
12. Karana, E., Barati, B., Rognoli, V., Zeeuw van der Laan, A.: Material Driven Design (MDD): a method to design for material experiences. Int. J. Des. **9**, 35–54 (2015)
13. Ostuzzi, F.: Open-ended design. Explorative studies on how to intentionally support change by designing with imperfection (2017)
14. Camere, S., Karana, E.: Fabricating materials from living organisms: an emerging design practice. J. Clean Prod. **186**, 570–584 (2018). https://doi.org/10.1016/j.jclepro.2018.03.081
15. MacArthur, E.: Towards the circular economy. J. Ind. Ecol. **2**, 23–44 (2013)
16. Rognoli, V., Bianchini, M., Maffei, S., Karana, E.: DIY materials. Mater. Des. **86**, 692–702 (2015). https://doi.org/10.1016/j.matdes.2015.07.020
17. Vandenbroeck, P.: Working With Wicked Problems, pp. 1–50. King Baudouin Found (2012)
18. Rognoli, V., Ayala-Garcia, C.: Aversa H DIY-Materials. Technological Approach of Materials for Design, pp. 1–7
19. Vert, M., Hellwich, K.-H., Hodge, P., et al.: Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). Pure Appl. Chem. **84**, 377–410 (2012)

20. Lynn University Research Methods in the Social Sciences - Exploratory Design. http://lynn-library.libguides.com/c.php?g=549455&p=3771805. Accessed 16 Dec 2018
21. Karana, E.: Meanings of Materials. Delft (2009)
22. Pacelli, F., Ostuzzi, F., Levi, M.: Reducing and reusing industrial scraps: a proposed method for industrial designers. J. Clean. Prod. **86**, 78–87 (2015). https://doi.org/10.1016/j.jclepro.2014.08.088
23. Technical Committee: ISO/TC 207/SC 5 Life cycle assessment: ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework (2006). https://www.iso.org/standard/37456.html. Accessed 8 Dec 2018
24. Antony, U., Edward, J.: Flourishing Enterprise Innovation – Tools for the Strongly Sustainable Revolution – Financially Rewarding, Socially Beneficial, Environmentally Regenerative. http://www.flourishingbusiness.org/
25. Karana, E., Hekkert, P., Kandachar, P.: A tool for meaning driven materials selection. Mater. Des. **31**, 2932–2941 (2010). https://doi.org/10.1016/j.matdes.2009.12.021
26. St Clair, K.: The Secret Lives of Color. Penguin (2017)
27. Haneef, M., Ceseracciu, L., Canale, C., et al.: Advanced materials from fungal mycelium: fabrication and tuning of physical properties. Sci. Rep. **7**, 1–11 (2017). https://doi.org/10.1038/srep41292
28. Hill, R.J., Osgood, C.E., Suci, G.J., Tannenbaum, P.H.: The measurement of meaning. Am. Soc. Rev. **23**, 227 (1958). https://doi.org/10.2307/2089024
29. Nagamachi, M.: Kansei engineering: a new ergonomic consumer-oriented technology for product development. Int. J. Ind. Ergon. **15**, 3–11 (1995)
30. Camere, S., Schifferstein, R., Bordegoni, M.: Materializing experiential visions into sensory properties the use of the experience map. In: Proceedings of the Tenth International Conference on Design and Emotion - Celebration & amp; Contemplation (2016)
31. Kauffman Jr, D.L.: Systems One: An Introduction to Systems Thinking. In: Innovation Learning Series, vol. 41 (1980)
32. Braun, W.: The System Archetypes, p. 27 (2002)

Hemp-Block Partition Panel Design and Life-Cycle Assessment

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Abstract. This study presents the first results of a research project aimed at creating prefabricated panels that consist of hemp blocks, to be used for closures and vertical partitions within load-bearing frames. With the study of the wall design, we wanted to provide high safety performance, as especially relevant for areas with high seismic risk (such as Italy), through the use of non-fragile products. The use of hemp blocks for prefabricated walls will also allow the development of strategies to: (i) reduce construction times; (ii) reduce decommissioning of buildings; and (iii) promote the use of sustainable construction products. Life-cycle assessment of hemp blocks (Canaplock) was also carried out. This study considers the ecological, economic, and social benefits of hemp, and transfers these to this new application. A comparison of the product conceived with similar products already on the market is developed, in particular for those with prefabricated straw and wooden panels. This study is the result of a collaboration between the world of research and the production sector, as it forms part of an industrial Doctorate. The results of this study will have an application outlet, as they will support the Canaplock manufacturer in the promotion and dissemination of the use of hemp-based products according to the criterion of sustainable development, especially as these can provide real benefits for the environment and the user.

Keywords: Hemp · Blocks · Prefabricated panel · Modularity

1 Introduction

Hemp (*Cannabis sativa* Linnée) is an angiosperm plant that has been cultivated from historic times [1] to today in many parts of the world, especially for industrial purposes. In Italy, hemp has an important past also as a traditional crop, although contemporary production is not yet widespread.

The stem of the hemp plant has a woody core that is surrounded by strong and long fibers that are extracted using a special process. These fibers have been used for millennia in the manufacture of paper, fabrics, and above all, rope (known as hawser). Today, hemp fibers are also used in the automotive industry, in the furniture industry, and for the last two decades, in the construction industry [2–4].

Hemp is a highly eco-sustainable plant, as it grows very fast [5, 6], has wide resistance to thermal variations [7], and has very little irrigation and fertilization needs [8].

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In addition, hemp plants have a low protein content, which protects them from attack by insects and moths, which also reduces the need for pesticide use [7]. A chemical analysis of hemp fibers reported by Sedan et al. [9] indicated the following constituents (wt%): pectin, 20.1; lignins, 6.0; protein, fat, waxes, and ash, 7.9; and cellulose and hemicellulose residue, 67.0.

The fibrous part of the hemp plant is used in the field of construction products, which represents about 40% to 60% of the entire plant [10]. In the specific case of the hemp blocks under study here, this fibrous part is mixed with binders (composition: hemp shives and natural additives, such as hydraulic lime), which provides a product with considerable advantages, especially considering also its high performance as a thermal insulator, and its high absorption of humidity [11].

For all of these reasons, the use of hemp blocks is spreading more widely in sustainable construction [9]. Furthermore, the study of new products and their introduction onto the market is certainly a source of design innovation. This aims at creation of new construction elements, speeding up of the production processes, reduction of environmental and economic costs, and improvement of internal comfort and safety of architectural spaces.

Further to this technological, environmental, social, and economic progress, for a material to effectively qualify as eco-sustainable, the products need to be studied not just from the point of view of their physical and behavioral characteristics. Such products also need to be certified through shared and dedicated processes, and must satisfy specific regulations. Thus, although hemp blocks and other hemp-based building elements are now sufficiently well known from a physical and behavioral point of view, they still need to be certified, particularly as confirmation of their regulatory compliance is still incomplete.

Framework of the Project:

1. Identification of the objectives.
2. Analysis of the intervention context and identification of the problems to which the project aims to respond.
3. Study of the state of the art of materials for green architecture (study of the state of the art in the European and Italian panorama) and choice of hemp as a building material.
4. Case study analysis of prefabricated wood-straw panels.
5. Prefabricated panels in wood and hemp block as a modality of design intervention (development of the concept).
6. Life-Cycle Assessment of hemp block.

2 Research Objectives

The main aims of this research project are the following:

1. Procurement phase: identification and study of strategies to promote the commitment to healthy products in architecture, with the possible use of 'zero distance' resources and the processing of renewable natural raw materials.

2. Production phase: optimization of the construction production processes. Identification and evaluation of the improvement indices of sustainability of products and their production processes (i.e., Life-Cycle Assessment [LCA] studies).
3. Building construction and deconstruction stages: reduction of time, costs, and complexity of the operations for setting up and decommissioning vertical closures.
4. Operating phase of the building system: increasing the performance of buildings through the use of hemp blocks. This aspect includes improvements to the internal comfort of houses (e.g., thermal, hygrometric), reduction of the environmental impact, and savings on energy consumption (in favor of the environment) and costs (in favor of the user).

The applicative impact of the entire project is to support the company that produces the hemp blocks, called Edilcanapa, for three particular aspects: (i) develop innovative solutions at the decision-making level that improve the production chain; (ii) facilitate communication of the performance of the product, with particular regard to its low environmental impact; and (iii) promote the diffusion of the product on the market.

3 Research Methods

3.1 Knowledge of the Problem

The research project stems from the constant and ever-growing concerns and attentions towards environmental problems. All of these aspects have led to the desire to undertake sustainable development, to ensure the progress of society and its well-being (i.e., living better, consuming less). This is a double value that leads us to better analyze the concept of sustainability, and to consider it a multidisciplinary concept that consists of the following three fundamental aspects, better known as the 'triple bottom-line' [13].

Environmental - For Environmental Sustainability
There is a need to decrease the environmental degradation that is in progress.

Economic - For Economic Sustainability
There is the need to invert the trends in the current conditions of the economic system.

Social - For Social Sustainability
There is the need to guarantee the development and well-being to the entire world population.

In recent decades, the concept of sustainability based on these aspects of the 'triple bottom-line' has also taken on importance in the architectural field, driven by the need to reduce the strong impact that building activities have on the system-environment during the entire life cycle of buildings (i.e., for the sequence of procurement of raw materials, construction, use, and disposal). In this regard, we must consider that in the 1990s, globally, the construction sector was classified as one of the most polluting and harmful to the environment [14].

Environmental sustainability in the building sector needs to include the relationships both between the natural environment and the built environment (i.e., the 'macro-environmental' relationships), and between the built environment and the inhabitants (i.e., the 'micro-environmental' relationships). For this latter, it is the user who asks for environments that are safe, comfortable, and healthy [2].

In response to these new environmental and human sensitivities and needs, the concept of ‘green building’ has developed. This is really nothing more than an approach to architecture, and indeed to all of the life stages of an architectural structure, that provides the least economic and environmental impact possible. Such a system is based on greater integration between the environment, the building, and the inhabitant, to reduce consumption (i.e., of land, raw materials, energy, money) and emissions into the environment, while ensuring continued comfort and well-being for the user.

It is clear that green building requires an integrated approach that has to pass through various choices and considerations, of which the main ones are: (i) choice of the construction site; (ii) climatic conditions of the site; (iii) choice of the energy source to support the energy requirements of the house; (iv) construction techniques to be used; and (v) choice of materials.

3.2 The Choice of Hemp in Response to Environmental, Economic, and Social Needs

The research work here is based on the choice of materials. This started from a broad look at the current solutions, in terms of eco-sustainable building materials, as alternatives to the present “*classic*” materials. At the European and Italian levels, these include reinforced concrete, bricks and steel, as well as various synthetic inorganic materials used for insulation at the thermo-acoustic level. The focus was therefore initially on an analysis of materials of plant and animal origin.

Considering that the objective of the research for this Doctorate project is the creation of prefabricated infill systems that can be used for new construction and recovery of pre-existing buildings, we focused on the analysis of hemp as a raw material. The advantages of hemp were thus initially evaluated in terms of its cultivation, noting also its high capacity to retain and absorb large quantities of carbon dioxide from the atmosphere, due to the cellulose content. Furthermore, the performance of hemp as a highly versatile building material that allows multiple uses is not negligible. Indeed, there are many products for construction that are made with hemp. Such uses of hemp as a raw material for building products can have enormous performance advantages. These place hemp-based construction products on the market as perfect substitutes for the other materials that are more commonly used in construction, not only in terms of parity, but also for superior performance [2].

Despite the many advantages of hemp in housing, it is not yet used on a large scale. The problem appears to be the lack of knowledge on the part of the designers and the workforce of the techniques for making the materials and for their installation.

Not only in Italy, but also throughout Europe, there is still a lack of specific structured legislation. However, the most important obstacle is probably a lack of understanding of the differences between the different plant species of hemp. In particular, this leads to confusion between *Cannabis sativa* (the only hemp that has building applications) and *Cannabis indica* (the medicinal and hallucinogenic hemp). From this confusion there follows a skepticism towards the use of hemp in construction. This situation results in difficulties for the possibility of freely cultivating industrial hemp plants in some countries, so that often the raw materials have to be imported instead. As might be expected, this comes with increased production costs. In addition, the importation of the raw material partially cancels out the positive environmental impact that hemp can offer as a building material, in terms of a ‘zero-distance’ material; i.e., one that is without significant impact from the problems related to long-distance transport [10, 15].

3.3 Comparisons and Design References

To achieve the final objective of the PhD research here, namely the identification of standards and the design and construction of prefabricated panels for dry infill wall, we proceeded to the identification, analysis and comparison with prefabricated panels already available on the Italian and European markets. Wood-straw panels were identified and defined as the reference, as they are the products that are closest to the new system being designed.

Two patents were selected and considered for more in-depth analysis in this study: ModCell[1] and Pablok[2]. Both of these materials are currently used for external walls and internal partitions for buildings. They are dry prefabricated panels that combine straw (a traditional green material) from the agricultural sector with modern construction methods. These can thus provide for green building with very low environmental impact.

The ModCell panel, in particular, was patented in the United Kingdom, and as the patent indicates, it is a type of panel that can be applied either as a structural element or as a simple infill element. This allows the construction of ‘passive’ buildings, due to the high thermal insulation capacity of these panels, with substantial savings in economic terms for energy bills, through reduced thermal energy dispersion into the environment [16].

Indeed, buildings made with the ModCell system are characterized by negative carbon emissions. This is possible due to the composition of the product, which is made up exclusively of sustainable zero-distance materials, particularly as the factories for manufacturing these panels are located within a radius of 15 miles from the construction sites. The materials that go into the ‘core’ of the ModCell panels include the following: (i) straw bales for the infill; (ii) Forest Stewardship Council (FCS)/Programme for the Endorsement of Forest Certification (PEFC) wood for the construction of the structural frame; (iii) metal uprights to stabilize the panels and to help provide support for vertical loads; and (iv) wooden slats to provide the anchoring of the closing elements and surface finishing of the individual panels [16].

Moving on to the Italian panorama, for the present study, the Pablok panels were taken as the reference model. These are a product that fully complies with the minimum environmental criteria (Criteri Ambientali Minimi [CAM][3]). In this case, the materials

[1] ModCell straw technology – company based at Hamilton House, Bristol (UK).

[2] Pablok green building – company based at the Milanofiori Business Centre, Rozzano (Italy).

[3] CAM - minimum environmental and ecological requirements to be observed mandatory by law (introduced in art. 18 of Law 221/2015 and in art. 34 containing “Criteria for energy sustainability and environmental” of Legislative Decree. 50/2016 “Procurement Code” (amended by Legislative Decree 56/2017), for all contracting stations. In order to be able to identify the design solutions (projects/products/services) correct from an environmental point of view, to reduce the environmental impact and promote sustainability, the use of green solutions and the circular economy, allowing the Public Administration to reduce consumption and expenses.

used for these prefabricated panels consist of the following: (i) pre-treated compressed straw for the filling; (ii) laminated fir wood for the structural frame; (iii) wooden internal uprights to stabilize the whole panel; and (iv) gypsum fiber [17].

The two products used for this comparison and briefly described above appear to be panels with very low environmental impact and with excellent performance in use. In addition, they are lightweight construction solutions. In particular, the lightness of this prefabricated cladding is a further element that is of fundamental importance for the safety of users, especially in seismic areas. Indeed, the damage to property and person in the event of collapse of built structures during earthquakes is proportional to the weight of the collapsing structure. Therefore, light construction components based on the use of vegetable elements with low specific weight (such as straw and hemp) are also preferable in this sense.

4 State of Progress of the Research

4.1 Choice of Product, Interaction with the Company, and Design of the Panel with Hemp Blocks (Study and Promotion)

Starting from the technical information for the wood and straw reference panels, I worked on the hypothesis of technology transfer to prefabricated hemp products. To develop the most advantageous solution based on possible intervention scenarios, and considering that part of the basic objective of the PhD project was to interact with local companies and develop the study internationally, we focused on products and companies present in the panorama of the region of Abruzzo (in Italy; specifically, we are working with the company Edilcanapa Srl, of Teramo) [2, 12]. The hypothetical ‘hemp-based prefabricated panel’ product should find its major and versatile building applications in the following fields:

- *renovation of existing buildings:* in which sustainable solutions can be used to reduce the global impact that the building has on the environment;
- *additions to existing buildings:* with improved performance in terms of energy efficiency and safety for users;
- *new buildings.*

In these areas, totally or partially natural materials can be used that in addition to giving a building a lower environmental impact, also positively influence the comfort of the internal environments and the safety of the users, even in the event of an earthquake. Considering the potential of earthquakes, it is possible to use such panels to replace the traditional perforated brick infill (which is easily subject to collapse, and therefore certainly represents a danger to the inhabitants, with natural products (such as hemp blocks).

The choices between the possible different solutions will be based on the evaluation of a sum of factors, to arrive at a weighting of all of the aspects involved, which will include the following in particular: materials and uses with low environmental impact; compatibility with pre-existing structures; internal comfort; and user safety.

Theoretically, there are two ways to achieve a product that has all of the aforementioned characteristics: (i) prefabricated hemp panels using a single cast, of metric dimensions; and (ii) hemp panels resulting from the assembly of hemp 'bricks' that are already in production, of decimeter dimensions. The first option here has some theoretical disadvantages, among which we can list at least: the need to build large molds for the castings; the high drying times (in the factory) that are related to the large mass of cast material; the bending moment and breaking point of the large panels imposes the need for extra thickness [15], or alternatively, imposes the need for a dense load-bearing weave of wooden strips; and the modularity characteristics of the versatility of the prefabricated panels in an inversely proportional manner with respect to the dimensions of the single cast panel. All of these considerations represent real critical issues that risk significantly reducing, some of the advantages of such prefabricated panels for infill wall.

To overcome this criticality, the assumption is for a wooden frame to be created, inside which the individual hemp blocks will be positioned that are already in production by the company (*Canaplock*; Edilcanapa Srl). Creation of such modular construction elements (which have the function of infill wall only) will allow easy and fast installation and disposal. Also, being modular structures, the panels will allow easy adaptation to any situation, such as creating corners and openings for doors and windows.

Regarding the characteristics of the *Canaplock* hemp blocks, comparative studies have already shown that these must have different technical characteristics that depend on the building structures in which they are to be used. Indeed, the proportions between hemp fiber and binder (and consequently, the density of the final material) need to be different, depending on whether the mixtures are used for construction of roofs, walls, or floors [8]. In particular, 110 kg of shive and 220 kg of binder for each cubic meter of hemp fiber need to be used for the preparation of the hemp blocks intended for the construction of walls, which leads to a final density of 330 kg/m^3 [14].

Overall, and also taking into account these technical indications, the design concept aims to combine the high performance of hemp with the lightweight prefabricated construction systems (considering that the weight of hemp is about one seventh or one eighth that of concrete) [18]. In this way, it will be possible to create construction systems that are durable over time, and are recyclable (i.e., potential for end-of-life recovery) and biodegradable, refractory to mold and insects, and fireproof. They will also provide optimal thermal-acoustic insulation, high thermal inertia, and resistance to frost damage, while being highly breathable. Finally, they will help in the regulation of the thermal-hygrometric structure of the rooms, due to the thermal inertia and absorbance and release of environmental humidity by the hemp, which will create healthy internal spaces and avoid damage to the material itself due to deterioration caused by humidity.

Of note, hemp is a negative carbon material; i.e., it can absorb carbon: 325 kg of CO_2 can be captured by a ton of dry hemp [19]. Moreover, hemp can reduce the CO_2 in the atmosphere [20]. This means that these panels will also help reduce air pollution and the greenhouse effect, creating a 'carbon-free' building. Furthermore, assuming the panels as a hybrid product between a light and a heavy system, this will contribute to the realization of constructions that can better resist seismic events. Finally, a saving in terms of space can also be assumed; as hemp bricks are a naturally thermal insulating product, it will not be necessary for the addition of any further elements to the total thickness of the panels.

The hemp blocks also lend themselves to being the basis of the finishing layers of the wall surfaces, as for plaster and paint. The use of hemp-based finishing products will be preferable to implement the excellent performance of the underlying panel, ensuring breathability to the entire finished element, and preserving its characteristics. In this way, it will be possible to have a complete solution, from the structure to the surface finish.

4.2 Life-Cycle Assessment of Hemp Blocks

In agreement with the partner company, it was decided to apply LCA, because it is the only coded tool that is recognized internationally that can be used to assess the environmental impact of the analyzed product. It is used to identify, quantify, and evaluate the impacts through all phases of the product life cycle, considered within specific contexts. This is achieved by evaluation of the relationships that the product under analysis has with the surrounding environment, in terms of the incoming and outgoing flows (i.e., the input/output) during each phase.

The LCA assessment consists of four consequential phases. At the present stage of the Doctoral research, the LCA assessment is still underway. These phases are detailed in the following:

Phase 1 – The objectives and scope of the evaluation have been defined. The objective will be to verify and certify the environmental qualities of the product, underlining the strengths and any shortcomings or criticalities of the hemp blocks, to confirm that they represent a green, eco-sustainable and environmentally friendly product within the phases of the life cycle considered. This will also encourage its diffusion on the market. The LCA assessment will be carried out exclusively using module A, for the production of the product, including the phases of supply, transport to the factory by the company (Edilcanpa Srl), and processing for the realization of the hemp blocks. Assumptions will be made on the possible end-of-life scenarios of the product (module C), while all of the other phases of the LCA assessment are excluded from the present analysis (see Fig. 1). One month of production (March 2021) has been identified as the functional unit on which to carry out the LCA assessment. This appears an anomalous choice, but the company has revolutionized its production plant in recent months, with the complete updating of its machinery to make use of the latest technologies. The suppliers of the hemp have also changed, with a move from French companies to Italian companies for the supply of the raw material from local *Cannabis sativa* plantations. This has thus drastically reduced the impact associated with transport. All of these updates carried out over the last year by the company have thus led to a general lack of historical data on the production (i.e., the data available are now outdated, and would not represent a relevant assessment of the current state of affairs). It is for this reason that it was decided to monitor the company production process by limiting this to the month of March 2021 only: so as to base the LCA assessment on up-dated data.

Phase 2 – Inventory analysis. All of the inputs (i.e., raw materials, water, energy) and outputs (i.e., emissions into the atmosphere, water, soil) through all of the phases of the life cycle subject to study have been defined (module A).
Phases 3 and *4* – Evaluation of the life-cycle impacts (phase 3) and interpretation of the results of the LCA evaluation (phase 4). At present, we are waiting to receive all of the data required to be collected directly from the company for this reference month, to be able to continue the work and complete these two phases.

PRODUCT stage			CONSTRUCTION PROCESS stage		USE stage							END OF LIFE stage				BENEFITS AND LOADS BEYOND THE BOUNDARY OF THE SYSTEM
Rew material supply	Transport	Manufacturing	Transport from the gate to the site	Construction-installation proces	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
x		x														x

Fig. 1. Phases and modules for Life Cycle Assessment (LCA): only the modules highlighted in green will be treated for the assessment of the LCA of hemp blocks.

5 Work in Progress and Expected Results

This study for the design, prototyping, and production of prefabricated panels using hemp blocks for the construction of internal infill panels and partitions is still underway, although the following results can already be indicated.
1 – The focus has been on the eco-environmental and bio-architectural reasons that led to the choice of hemp as a fully bio-sustainable material, not only for the improvement of the natural environment *versus* the built environment, but also for the built environment–inhabitant relationship. Indeed, in terms of the built environment, this is particularly important in central Italy, which is an area with high seismicity. Thus, with the promotion and spread of the use of panels of prefabricated hemp, in the case of collapse of buildings, there will be more limited damage to people and materials.
2 – Definition of the characteristics of the dough necessary for the formation of the panels that are to be used for the realization of the specific hemp blocks for walls.
3 – Identification of the prefabricated panels based on straw (already on the market) as elements for comparison with the prefabricated panels based on hemp (in the design phase). The comparisons have shown the strengths of the new product, especially in terms of the low environmental impact during production, the greater efficiency as a thermal and acoustic insulator, and moreover, the benefits as a CO_2 consumer material.

4 – Choice of the preparation of the prefabricated panels by assembling pre-built hemp blocks using special wooden slatted grids, rather than the use of a single hemp casting. This allows for further savings in the manufacturing phases, and further ease in the transport, handling, and installation phases. Furthermore, it has advantages in terms of construction versatility, for greater modularity.
5 – Development of the product concept, with identification of the support and containment materials (wooden slats), the filling materials (*Canaplock*, of appropriate thickness and with specific composition), and the modularity of the assembly scheme.
6 – To orient architectural constructions towards greater and broader-spectrum sustainability, and therefore environmental, economic, and social sustainability, it is necessary to consider the products/services/systems that make up the life cycle of these materials. Further, it is necessary to involve all of the possible and different actors during this cycle. To help us in this complex action, LCA is being carried out. Thus, in the context of the research discussed here, the evaluation of the life cycle of the central product is underway, which will be used to set up the hypothesized panels; i.e., the hemp blocks (*Canaplock*). This will also verify and certify its environmental qualities, as a green, eco-sustainable and eco-compatible product through all its life stages, to encourage its diffusion on the market.

To complete the project, completion of the following aspects is required: (i) the full details of the new product concept; (ii) the analysis and evaluation phase of the *Canaplock* LCA; (iii) the estimation of the times that will represent the savings linked to the use of prefabricated panels (both in the construction phase and in the demolition phase of the buildings); (iv) the characterization of the new final product for the purpose of information for users and widespread dissemination on the market.

All of these phases will also be carried out in concert with the company Edilcanapa srl (Teramo), which is currently collaborating on the project. They represent the application terminal for the prototyping, production, and marketing of the new product.

The expected results from the design and LCA assessment part of the hemp blocks (*Canaplocks*), and above all of the design of the hypothesized panel, will be exchanged and analyzed with the Institute of Sustainability in Civil Engineering (INaB), RWTH Aachen University in Germany. The exchange between the two universities and the company Edilcanapa will lead to the preparation of a detailed report on the LCA and S-LCA assessments relating to the Edilcanapa production process.

The expected outcome from this activity is a document of design recommendations that will be useful for validation of the product.

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References

1. Vavilov, N.I.: Origin and Geography of Cultivated Plants. Cambridge University Press, Cambridge (2009)
2. Radogna, D., Mastrolonardo, L., Forlani, M.C.: Hemp for a healthy and sustainable building in Abruzzo. In: Intelligent Human Systems Integration. Advances in Intelligent Systems and Computing, vol. 722, pp. 720–726 (2018)
3. Tewari, A.: Hemp – a sustainable building material. J. Civ. Eng. Environ. Technol. **5**, 327–332 (2020)
4. Mastrolonardo, L.: Progettazione ambientale a chilometro zero. Sostenibilità ed ecologia industriale per lo sviluppo di filiere edili [Zero kilometer environmental design. Sustainability and industrial ecology for the development of construction chains]. Maggioli, Rimini (2016)
5. Deitch, R.: Hemp: American history Revisited: The Plant with a Divided History. Algora Publishers, New York (2003)
6. Gross, C., Walker, P.: Racking performance of timber studwork and hemp-lime walling. Construct. Build. Mater. **66**, 429–435 (2014). http://dx.doi.org/10.1016/j.conbuildmat.2014.05.054
7. Demir, I., Doğan, C.: Physical and mechanical properties of hempcrete. The Open Waste Management Journal **13**, 26–34 (2020)
8. Burczyk, H., Grabowska, L., Kołodziej, J., Strybe, M.: Industrial hemp as a raw material for energy production. J. Ind. Hemp **13**(1), 37–48 (2008). http://dx.doi.org/10.1080/15377880801898717
9. Sedan, D., Pagnoux, C., Smith, A., Chotard, T.: Mechanical properties of hemp fibre reinforced cement: influence of the fibre/matrix interaction. J. Eur. Ceram. Soc. **28**, 183–192 (2008)
10. https://www.dolcevitaonline.it/nei-geni-della-canapa-le-differenze-morfologiche-tra-la-varieta-industriale-e-medicinale/. Accessed 29 Mar 2021
11. http://www.microscopy-uk.org.uk/mag/indexmag.html?http://www.microscopy-uk.org.uk/mag/artmay14/tk-Cannabis.html. Accessed 29 Mar 2021
12. https://www.edilcanapasrl.it/. Accessed 29 Mar 2021
13. Torricelli, M.C.: ES-LCA e patrimonio naturale: Life Cycle Analisi ambientale e sociale di un'area protetta, Firenze Università Press (2015)
14. Nováková, P.: Use of technical hemp in the construction industry. In: MATEC Web of Conferences, vol. 146, 03011 (2018) Building Defects 2017. https://doi.org/10.1051/matecconf/201814603011
15. Arrigoni, A., Pelosato, R., Melia, P., Ruggieri, G., Sabbadini, S., Dotelli, G.: Life-cycle assessment of natural building materials: the role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks. J. Cleaner Prod. **149**, 1051–1061 (2017)
16. https://www.modcell.com/technical/. Accessed 29 Mar 2021
17. https://www.gpproject.eu/bio-architettura/. Accessed 29 Mar 2021
18. Allin, S.: Building with Hemp. Seed Press, Rusheens, Kenmare Co., Kerry (2005)
19. Pervais, M.: Carbon storage potential in natural fiber composites. Resour. Conserv. Recycl. **39**(4), 325–340 (2003)
20. https://www.usidellacanapa.it/pdf/cemento_di_canapa_e_calce.pdf. Accessed 29 Mar 2021

Development of a Steering System for Parasport Sleds Using Lightweight Design and Additive Manufacturing of Fibre-reinforced Polymers

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Abstract. For some years now, additive manufacturing (AM) has offered an alternative to conventional manufacturing processes. The strengths of AM are primarily the rapid implementation of ideas into a usable product and the ability to produce geometrically complex shapes. It has also significantly advanced the lightweight design of products made of plastic. So far, the strength of printed components made of polymers is previously very limited.

Recently, new AM processes have become available that allow the embedding of short and also long fibers in polymer matrix. Thus, the manufacturing of components that provide a significant increase in strength becomes possible. In this way, both complex geometries and sophisticated applications can be implemented. This paper therefore investigates how this new technology can be implemented in product development, focusing on sports equipment. An extensive literature research shows that lightweight design plays a decisive role in sports equipment. In addition, the advantages of AM in terms of individualized products and low quantities can be fully exploited.

An example of this approach is the steering system for a seat sled used by paraplegic athletes in the Olympic discipline of Nordic paraskiing. A particular challenge here is the placement and alignment of the long carbon fibers within the polymer matrix and the verification of the strength by means of Finite-Element-Analysis (FEA). In addition, findings from bionics are used to optimize the lightweight design of the steering system. Using this example, it can be shown that the weight of the steering system can be drastically reduced compared to conventional manufacturing. At the same time, a number of parts can be saved through function integration and thus the manufacturing and assembly effort can be reduced significantly.

Keywords: Lightweight design · Additive manufacturing · Sustainable product development · Design for fibre reinforced AM

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1 Introduction

In additive manufacturing (AM), in contrast to conventional, subtractive manufacturing processes, the material is applied layer by layer to a base plate. Additive manufacturing processes work without tools and without a mould. The volume of an object is built up in three dimensions according to a digital computer model. This offers the possibility to realize individual geometries in products without additional effort.

Fused Deposition Modelling (FDM) is an established AM process for the production of thermoplastic components. In this process, the material is heated in a nozzle and built up layer by layer to form the desired component. The advantages of the FDM process are its accuracy of ±0.1 mm, good reproducibility, and the fact that it can be used with engineering plastics such as ABS, PC and high-performance plastics. The high accuracy is achieved by the position-controlled feed drives of the FDM head. These are comparable to machine tool drives, but the nozzle diameter on the print head limits the mapping of fine details [1].

1.1 Fibre-Reinforced Additive Manufacturing

Additive processes can be used to create lightweight components with customized geometries. Compared with conventional processes, however, their mechanical stability still needs to be improved. In principle, carbon or glass fibres are introduced into the base material, the so-called matrix, for reinforcement. In addition to the method that embeds short microfibers in the matrix, there is also the option of using long, continuous fibres. This second option requires a special printing process to embed high-strength, long fibres such as carbon, Kevlar or glass fibre. The Fibre Reinforced Additive Manufacturing (FRAM) process requires an additional extrusion nozzle to apply the fibre. The 3D printer actively switches between two nozzles during the printing process in order to automatically produce robust fibre-reinforced plastic parts in just one build process.

The fibre direction should be determined in such a way that the forces in the component run along the fibre, since such fibre-reinforced composites exhibit very high stability in the fibre direction. In fibre composites, the mechanical properties depend on the fibre direction [2]. This property of the fibre-reinforced plastic to withstand very high loads in the fibre direction, but to remain at the lower level of the matrix material perpendicular to it, is described as anisotropy. This property is not only found in the modern additive manufacturing process, but also in well-known building materials such as wood. However, anisotropy can basically be found in all additively manufactured products, even if no fibre reinforcement is used [3].

This results in special requirements for the design process. In conventional mechanical engineering, metals are often used in the subtractive manufacturing process. These components have almost identical material properties in all spatial axes. In the additive manufacturing process, anisotropy must be considered both in the design and in the positioning of the component on the printing platform [4]. The designer not only designs the part itself, but also the material. He can choose the fibre material, the amount of fibre, and the fibre orientation of each layer [2, 4].

1.2 Application Examples for AM in Sports

Sports shoes are among the first 3D-printed sports articles. But tennis rackets and various individual protective clothing such as crash helmets or shin guards can also be found as individual, additively manufactured products in top-level sport. Their most important advantage is the individual adaptation to the respective athlete. In addition, the materials can be used in a more targeted and economical way by means of 3D printing [4]. In the following, selected application examples of additive manufacturing in the sports sector will be presented, each of which represents the advancing state of the art, but also illustrates the lightweight design potential [6].

In cycling, aerodynamics plays an important role as speed increases [7]. An optimised handlebar was developed for the world hour record set by professional cyclist Bradley Wiggins in 2015. This prototype is based on the well-known time trial handlebar benefits form the freedom of geometry design of the AM. In this way, it was possible to achieve the optimum in terms of both ergonomics and aerodynamics with regard to the outer shape. The handlebars were produced from titanium using an Electron Beam Melting (EBM) process. Even though this bicycle handlebar does not use the FRAM process, the advantage of the individual geometry design of 3D-printed components becomes particularly clear.

At the 2018 Winter Olympics, the US team used additively manufactured luge sleds. This involved the AM of ergonomically and aerodynamically optimised individual parts from fibre-reinforced plastic. The great advantage here was the fast production as well as the individual adaptation to the respective athlete [8]. Traditional methods of manufacturing composite materials in particular are time-consuming and expensive. This example underlines the outstanding freedom of the designer in the geometry design of additively manufactured components and also uses the fibre-reinforced FDM process, which is also used in this project work.

Arevo, a young start-up company from California, was the first bicycle manufacturer to present an e-bike with a printed carbon frame in 2019. The frame is produced as a single part using the direct energy deposition process with the "multi-axis robotic motion system". With the help of the "Aqua 2" printer, which has been improved in the meantime, it is possible, according to the company, not only to produce particularly light and shock-resistant bicycle frames, but also custom-made according to the size and riding style of the customer [9].

1.3 Lightweight Design Using Bionics

The great lightweight design potential of AM was already demonstrated in 2016 in the "Light Rider" concept, a project by Airbus AP Works. By means of topology optimisation and FEM simulation, it was possible to print a motorbike frame from a special aluminium powder, the high-performance material "Scalmalloy", with a weight of only 6 kg. The challenge is not in the actual production process, but rather in the prior, optimal design of the components [10]. A basic bionic principle was followed: Within a bone, the structures form in such a way that pure tensile or compressive forces are transmitted. Where there is no force flow, the biological material is degraded. On the other hand, the bone is strengthened in places that are subject to high stress. The principle of the 45°

tension triangle also comes from nature. It avoids stress peaks in the component in a simple way and thus helps to optimise the geometry [11].

Sports equipment is only optimal if it is adapted to the respective conditions. The idea of lightweight design plays an important role in all sports, especially when the athlete has to overcome differences in height with his sports equipment [8, 12]. In para-sports, the weight of the sports equipment plays a particularly important role, since athletes with paraplegia or amputations often have a low body weight.

2 Product Development for Fibre-Reinforced AM

In the first step, the initial situation for the application example is briefly described. Then the steps in the product development process for FRAM are explained, with particular attention being paid to the special requirements for fibre reinforcement.

2.1 Boundary Conditions in Para-Sports

Paraskiing Nordic and Para biathlon are Olympic disciplines in disability sports. Paraplegic athletes need a seat sled that firmly encloses the paralyzed legs up to the hips like a ski boot. In this way, the still-functioning upper body can control the skis, which are firmly attached to the seat sled. Athletes steer by shifting body weight and sliding the skis sideways over the snow. In summer, or when there is no snow, the skis are replaced by ski rollers. These can be used to train on firm surfaces, usually asphalt. However, sit sleds with conventional ski rollers cannot be steered, the athlete can only lift the front of the sled to change the direction of travel. Therefore, in this paper a steering system for seat sleds developed.

The para-athletes who use this special sled have a body weight in the range of 33 kg to 50 kg. Comparable athletes without a handicap weigh almost 70 kg in endurance sports, and the seat shell is completely omitted for them. While a 33 kg para-athlete has to move about one third of his own weight with a seat sled weighing a total of 10 kg (seat shell 5.5 kg; steering system 4.5 kg), a 70 kg athlete only needs roller skis weighing 2.5 kg, which is less than five percent of his own weight. The aforementioned examples of AM applications show that not only individual customisation, but also the idea of lightweight design can be excellently implemented with the help of additive manufacturing.

2.2 Requirements for the Steering System

The original prototype of sled is made of square carbon tubing with an aluminium steering system basically works as shown in Fig. 1. The dimensions of the frame are limited by the wheelbase of approx. 890 mm and the predefined position of the ski binding. The ski binding represents the connection with the individual seat shell. The transverse distance between the two bindings is 230 mm, the height above the ground 60 mm.

The 45° inclination of the steering system couples two spatial axles with each other in such a way that a lateral inclination of the sports equipment leads to a steering lock of both axles. They are made of aluminium profiles with 5 mm wall thickness. The prototype weighs 4.6 kg in the current version with carbon frame and is therefore still too heavy

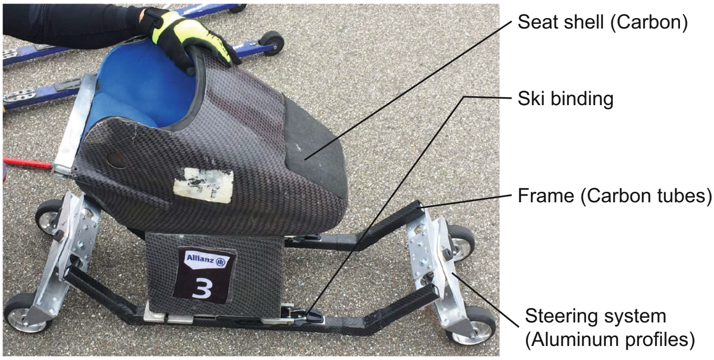

Fig. 1. Original seat sled with steering system made of aluminium profiles.

for daily training use. A conventional pair of roller skis weighs about 2.5 kg. The current prototype fulfils the steering behaviour desired by the athletes. So, the most important aspect is the reduction of the total weight. Due to the mostly congenital paraplegia, the athletes weigh between 33 kg and 50 kg. Therefore, the lowest possible weight of their sports equipment is extremely important for the acceptance and thus the regular use of the steering system in everyday training.

2.3 Geometry and Fibre Alignment of the Steering System

Due to the high cost and weight of AM components made of metal, e.g. by means of selective laser melting (SLM), a polymer-based additive process was chosen. A process involving the insertion of prepags (e.g. by means of robots) was not used due to the high cost of moulds and the long production time. The developed system is therefore based on the previous concept and attempts to optimise the weight with the help of the advantages of FRAM. An iterative approach is taken after the design of the variants. First, a variant with a framework structure was developed (see Fig. 2a). The recesses in the framework have the task of making the design lighter without losing strength.

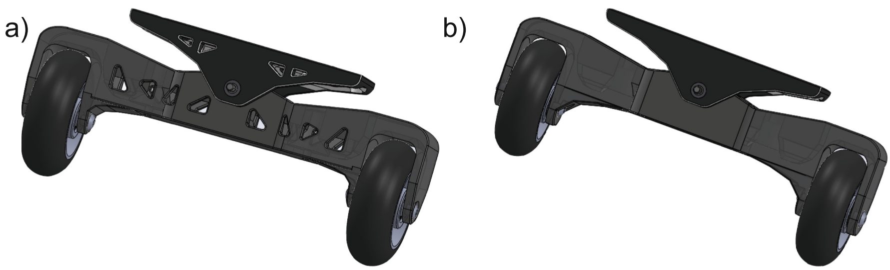

Fig. 2. CAD design of the steering system: a) with framework and b) in solid design.

During the development of the fibre reinforcement, however, it became apparent that these recesses lead to a less than optimal distribution of the long fibres. Figure 3a shows that many areas in the cross-section of the beam cannot be filled with fibres or can only be filled insufficiently. Due to the restrictions in filling and orientation, the areas near recesses and holes and in narrow geometries can only be reinforced with long fibres to a limited extent. If the framework is replaced by a solid design (Fig. 2b), the filling and orientation of the fibres is much less restricted. Thus, the strength can be significantly increased without having to accept a substantial increase in weight (see Fig. 3b). This complex workflow from current design to Design for Fibre-Reinforced AM (DfAM) illustrated in Fig. 4.

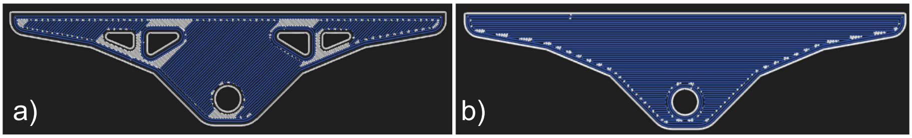

Fig. 3. Distribution and orientation of the long fibres (blue) of the bearing (upper part) in section: a) for framework with voids (white) and b) for solid design.

2.4 FE Analysis and Optimisation of the Steering System

In order to evaluate sufficient strength and safety of the weight-reduced steering system, a Finite-Element Analysis (FEA) is carried out using ANSYS for the bearing (upper part, Fig. 5a) and the wheel trunk (lower part, Fig. 5b). The meshing is carried out with an element size of 3 mm. This results in 81168 nodes and 52718 elements for the upper part and 218343 nodes and 142394 elements for the lower part.

In order to consider extreme driving situations at maximum load, a safety factor of S = 3 is applied to the acting force, resulting in the force of 1680 N to be used for the analyses. In the area of the wheel mounts and the transition to the wheel housing, very high stresses of over 60 N/mm^2 initially occur during the FEA. To reduce this, the transition to the wheel housing can be strengthened by constructive design using generous 45° tension triangles in accordance with the bionic design. This reduces the stresses considerably.

A further design solution must be found for the stress at the wheel reception. The developed design of an inlay offers the advantage of being able to optimally adapt it to the requirements. An asymmetrical shape (Fig. 6b) can transfer the moment and only introduce it into the axle at the points where it is stable enough. This principle is known as the polygon design of shaft-hub connections. At the same time, the inlay offers a larger surface for transferring the load from the wheels to the trunk. This allows the stress on the matrix material to be further reduced.

Fig. 4. Workflow from current design to the Design for Fibre-Reinforced AM

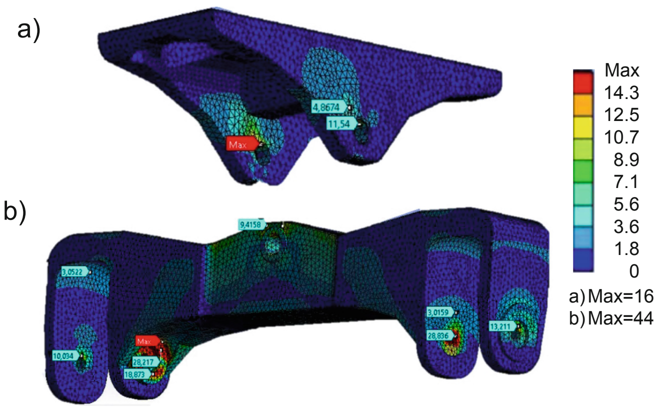

Fig. 5. Results of the von Mises stresses (in MPa) from the Finite Elements Analysis (FEA) for a) bearing (upper part) and b) wheels trunk (lower part).

For the transmission of the surface pressure of the bolts, an external overhang is designed, which distributes the contact pressure over a large area and transmits it to the trunk. Another advantage is that the inlay can basically be adapted to different wheel designs. For the inlays (see also Fig. 6b), material data aluminium is assigned from the An-sys database. For the printed parts of the axle, the material Onyx must be entered as in based on the material data from [13]. In order to take the laying of the fibre into account, the values for fibre reinforcement with a tensile direction 45° oblique to the fibre course are selected in the x-y plane of the printing platform. The tensile strength in the fibre direction is much greater, but the orientation of the fibre in each layer is oriented differently. This offers the best possibility of reinforcement for this design. A direct design of the fibre in the tensile direction is not technically feasible with the printing process used. In the z-direction, perpendicular to the printing platform, the strength is used without fibre reinforcement.

3 AM and Mechanical Testing of the Steering System

For this project, the Mark Two 3D printer from Markforged is used, which offers the possibility of embedding different fibres in the matrix material. Onyx is the matrix material (nylon) filled with short fibres. In this process, both the matrix plastic and the reinforcing fibre are printed simultaneously in Continuous Filament Fabrication (CFF). While short fibres are remarkable in their ability to reinforce thermoplastics, continuous filaments can add far more strength to components. This process uses a combination of FDM and CFF to deposit long strand fibres in conventionally printed thermoplastic parts. The fibre is already surrounded by a small amount of plastic from the manufacturer so that it bonds optimally with the base material during printing. First, a layer of matrix plastic is printed [13]. Then the fibre reinforcement is applied to this layer directly afterwards. The assembled product steering system is shown in Fig. 6a. In addition, Fig. 6b shows the inlay in polygon form made of aluminium.

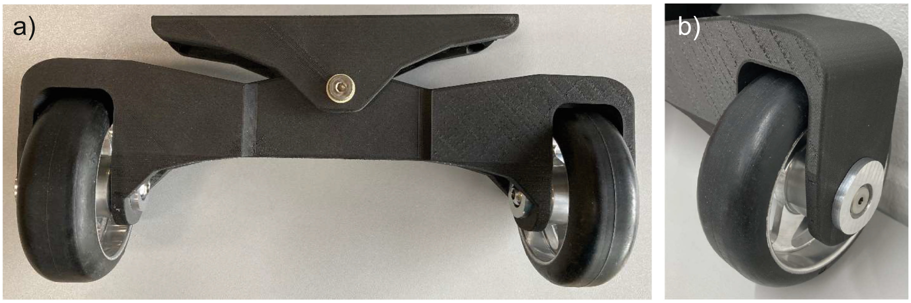

Fig. 6. Additively manufactured steering system (assembly): a) front view with connecting screw and b) side view with inlay (aluminium)

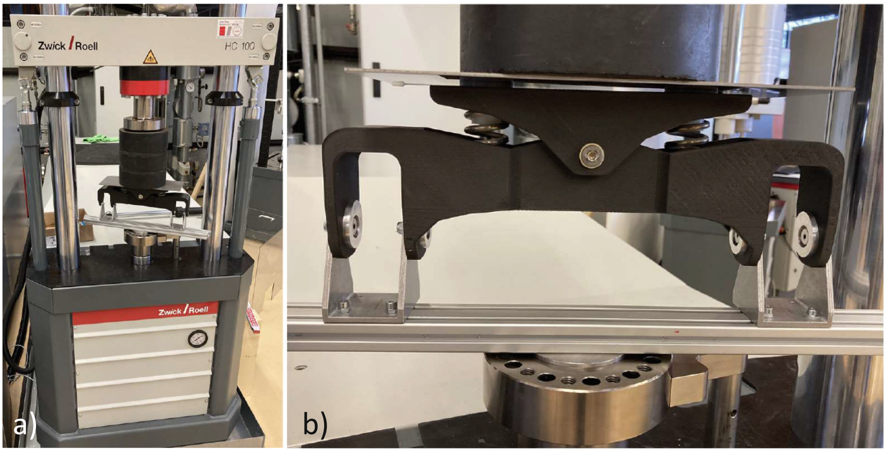

Fig. 7. a) Test setup for testing steering system (lower piston is moved; force sensor on top) and b) detailed view of the mounted system

A hydraulic testing machine HC100 from Zwick/Roell is used for the dynamic testing of the steering system. This is designed for forces up to 100 kN and has a sufficient measuring accuracy of 10 N (see Fig. 7a). The force sensor is mounted on top, the lower test plunger is moved hydraulically. Thus, the forces run through the steering system. The test sequence is controlled via the force control. A dynamic load of F = 1680 N is applied in a pulsating manner. The test is carried out with a frequency of 5 Hz over a duration of 35000 cycles. The wheel supports are clamped in a fixture with the same bolts as used for the usual wheel mounting, as shown in Fig. 7b. The upper part is connected to the test stamp by means of a metal plate.

The test is carried out with inserted springs in order to make the test as realistic as possible. The preload required for the pre-tensioning of the springs is 170 N. This increases the maximum force to be applied by the testing machine to 1850 N. During the dynamic test there is no noticeable deflection of the steering system. Based on the

FEA, up to 1 mm of deformation would have been expected. After the test, the steering system shows no visible damage and no permanent deformation.

4 Technical and Economic Evaluation

The weight of the fully assembled steering system is 421 g when weighed without wheels and springs. The weights of the individual parts are shown in Table 1. The finished pressure parts weigh slightly less than predicted by the Slice software during pro-cessing. In total, 705.8 g or 62.6% of the partial weight of the steering system can be saved per axle with the new, additively manufactured design. For the completely assembled seat slide, this means a weight saving of over 30% in relation to the total weight of the conventional design of the original seat sled (see Fig. 1).

Table 1. Comparison of weights.

Weights per component for one steering system	Conventional design (profiles made of Al) [g]	New design FRAM [g]
Bearing (upper part)	293.6	86.0
Wheel trunk (lower part)	415.8	261.0
Bolt with screw	161.3	32.3
Lower spring plate with screws	98.6	n/a
Trunk (U-Shape)	157.6	n/a
Inlays (Aluminum) with bearing	n/a	41.8
Total weight [g]	**1126.9**	**421.1**
Weight saving [%]		62.6

However, the developed steering system still has to prove the necessary stability to ensure the safety of the athletes. The stability of the new design can be considered sufficient based on the test procedures carried out and the FEA. In particular, the endurance test on the hydraulic testing machine is considered to be meaningful. In addition, the FEA carried out offers further good results for a sufficient safety of the additively manufactured steering system despite the incompletely known material data. The drop and impact tests can only be carried out later, as can the safety tests on the complete sled. The fibre-reinforced printed parts account for the largest share of the costs. One complete steering system, the material costs for 3D printing amount to 156.60 euros. The printing time is 58.5 h, or about 2.5 days.

5 Summary and Outlook

Overall, with the help of FRAM, it was possible to design and manufacture a very light and yet sufficiently stable steering system. In addition to lightweight and high-strength materials, the targeted optimisation of the design is also important for lightweight design. Here, the use of bionic design (tension triangles) made it possible to achieve targeted reinforcement. In addition, the number of necessary components and thus the assembly effort could be significantly reduced through functional integration. At particularly stressed areas of the component, the necessary strength could be achieved through inlays. Here, the skilful design using a polygon form achieved an even load distribution and a good form fit. The steering ability of the new system corresponds to the design made of aluminium, as the functional geometry was not changed. The reduction in weight as the most important point of the task can be rated extremely positively with a saving of more than 700 g per axle compared to the predecessor model made of aluminium. This corresponds to a reduction of approx. 60% of the weight of the sub-component. The fully assembled sledge is expected to weigh approx. 3.2 kg and is thus more than 30% lighter than the previous model.

In the future, feedback from the athletes will also be an important aspect in the product development. Furthermore, the long-term durability of the system should be closely monitored. Additional weight reduction by optimising other components will also be investigated. A further issue is the simplification of the workflow, e.g. by integrating the orientation and the distribution of the fibres into the FEA. It will be also important to develop FRAM processes that allow a reinforcement perpendicular to the printing direction, i.e. between the layers and not only within the layers.

References

1. Gibson, I., Rosen, D.W., Stucker, B., Khorasani, M.: Additive Manufacturing Technologies. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-56127-7
2. Korkees, F., Allenby, J., Dorrington, P.: 3D printing of composites: design parameters and flexural performance. RPJ **26**(4), 699–706 (2020)
3. Parandoush, P., Zhou, C., Lin, D.: 3D printing of ultrahigh strength continuous carbon fiber composites. Adv. Eng. Mater. **21**(2), 1800622 (2019)
4. Zhang, P., Liu, J., To, A.C.: Role of anisotropic properties on topology optimization of additive manufactured load bearing structures. Scripta Mater. **135**, 148–152 (2017)
5. Kajtaz, M., Subic, A., Brandt, M., Leary, M.: Three-dimensional printing of sports equipment. In: Materials in Sports Equipment, pp. 161–198. Elsevier (2019)
6. Meier, M., Tan, K.H., Lim, M.K., Chung, L.: Unlocking innovation in the sport industry through additive manufacturing. BPMJ **25**(3), 456–475 (2019)
7. Chi, S., Pitman, J., Crouch, T., Burton, D., Thompson, M.: The application of body scanning, numerical simulations and wind tunnel testing for the aerodynamic development of cyclists. Proc. Inst. Mech. Eng. Part P J. Sports Eng. Technol. **106**(9) (2020)
8. Beiderbeck, D., Krüger, H., Minshall, T.: The future of AM in sports. In: Schmidt, S.L. (ed.) 21st Century Sports, pp. 111–132. Springer, Cham (2020)
9. Nickels, L.: Carbon fiber 3D printing propels bike development. Reinf. Plast. **63**(2), 93–96 (2019)
10. Schürmann, J.P., Rothe, F.: Materialoptimierung für die additive Fertigung - das Konzept Light Rider. Lightweight Des **9**(S2), 10–15 (2016)
11. Mattheck, C., Burkhardt, S.: A new method of structural shape optimization based on biological growth. Int. J. Fatigue **12**(3), 185–190 (1990)

12. Cooper, R.A., Cooper, R.: Rehabilitation Engineering: a perspective on the past 40-years and thoughts for the future. Med. Eng. Phys. **72**, 3–12 (2019)
13. Junk, S., Dorner, M., Fleig, C., Additive manufacturing of continuous carbon fiber-reinforced plastic components. In: Scholz, S.G., Howlett, R.J., Setchi, R. (eds.) Sustainable Design and Manufacturing 2020, pp. 149–159. Springer, Singapore (2021). https://doi.org/10.1007/978-981-15-8131-1_14

An Open-Source Bioreactor Enhancing Microbial Cellulose Production and Novel Sustainable substances

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Abstract. Biodesign is a flourishing field which exemplifies a radical shift in designer's role and a changing approach towards materials, processes and systematic thinking. Instead of choosing among conventional materials and manufacturing processes, designers actively engage in developing new alternative materials by exploring the potential of living organisms as integral part of the process. This emerging field of design brings the need of new tools and enhanced knowledge transfer crossing diverse disciplines to investigate novel sustainable and alternative materials, production systems and scenarios. InnoCell is a design-led interdisciplinary research project exploring Microbial Cellulose (MC) that can be obtained through the fermentation of local apple-related byproducts with a culture of bacteria and yeasts (SCOBY). By turning 'waste' into novel sustainable substances, the project envisions a production system facilitating and optimizing MC production through open-source cultivation protocols and tools. This would optimize its knowledge transfer, support local small-scale iterations as well as possible industrial scale-up. This paper addresses the iterative development of a bioreactor module (InnoCell Bioreactor) for MC cultivation process based on residues of industrial apple processing. As such, it emphasizes the role of open-source design in raising new sustainable practices to 'grow' materials within more circular and distributed systems while fostering local resilience. Furthermore, the potential of locally recovered agri-food waste gives rise to novel applications of MC as edible and non-edible substances.

Keywords: Microbial cellulose · Growing design · Fermentation · Rotating disk bioreactor · Material production · Open source

1 Introduction - Microbial Cellulose and Its Sustainability Aspects

Cellulose is currently used in building, fashion, food, fuel, hygiene, medicine, packaging, paper, wood industries defining one of the biggest business and material flow. It is generally extracted from plants through diverse mechanical and/or chemical processes and its overall life cycle has considerable environmental repercussions [1] like high carbon emissions, eutrophication or soil impoverishment. In view of these aspects, alternative

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and more eco-efficient ways to generate and manufacture cellulose become worldwide relevant for future production and consumption perspectives. Microbial cellulose (MC) is a typology of cellulose which is secreted by several species of single microorganisms and appears in the state of translucent jelly biofilms or ribbons. However, cultures of cooperating bacteria (like Komagataeibacter xylinus) and yeasts (Saccharomyces Cerevisiae) called SCOBY (Symbiotic Colony Of Bacteria and Yeasts) have proven to provide better MC properties [2]. SCOBY, being an acetic 'mother' is renowned for being used for edible purposes namely, to brew the Kombucha beverage, which is a fermented green/black tea, and to produce Nata de Coco from coconut wastewater, a low calories and fiber rich dessert which is popular in the Philippines [3], Vietnam, Thailand and Indonesia [4]. The jelly-like biofilms can be processed into diverse substances that could be either edible, or not, ranging from powder to flakes and sheets, from gel to foam and composites. Being characterized by a three-dimensional fiber-configuration, a hydrophilic capacity and nutritional properties, MC is suitable for diverse applications such as food-ingredients (prebiotic, integrator, fat replacer, texturizer) [5, 6], (non)edible materials (filler, emulsifier, compostable substances), products like single-use packaging, cosmetics, components for electronics, medical and pharmaceutical applications [7, 8]. MC is made almost entirely of nanofibers [9] and its cellulose content is purer in comparison to the one extracted from vegetative sources. Moreover, MC production appears to be more sustainable and resource-efficient when comparing the two typologies [10]. MC is cultivated or 'grown' as microorganisms nourish on the nutrients present in a liquid medium and secrete fibers of which volume is multiplied up to centimeters in thickness. Tea and sugar are commonly used to feed SCOBY however, they are very production-expensive so, other water-based nourishments can be prepared with diverse carbon (sugar containing) sources [11, 12]. It was investigated by diverse scholars that liquid medium prepared substituting virgin sugar with food-production byproducts like molasses and pomace, were suitable and effective for SCOBY fermentation [7, 13]. This practice of further utilizing 'waste' would not only enhance the inherent value of primary resources but would also lower production costs, introduce profitable upcycling processes fostering local production possibilities. Circular production systems revaluing waste can improve current linear production cycles where valuable substances are systematically not used for their full potential and are down-cycled. Indeed, the implementation of MC production could foster a more conscious use of resources generating a positive ecological and even social impact by reducing the total dependence on import, while supporting local economic resilience [14]. As an alternative to the current dichotomy of 'products' and 'byproducts' a new production axiom could be introduced by considering all substances involved in the process as 'co-products' with generic equal value, enhancing the recognition of the primary value of resources [15]. Additionally, different agricultural crops provide diverse properties to MC biofilms and fermented liquid which can be used in various specific applications. Supporting this, data regarding structural determination of MC fibers and their impact on microbiota under simulated gastrointestinal conditions were provided by Micro4DFood team at the Faculty of Science and Technology of the Free University of Bozen-Bolzano. Their unpublished results generated by iterated comparative tests revealed that samples of MC grown from green tea appears to inhibit bacteria strains present in human microbiota and therefore its effects on human digestion range from neutral to negative. This finding suggests that tea-obtained MC is more suitable for non-food applications opening valuable upcycling perspectives for current disposed SCOBY mass generated from Kombucha production. However, MC grown from apple pomace-based broth showed presence of arabinoxylans -which are valuable antioxidants- suggesting promising perspectives in food applications as a prebiotic source. Antioxidants' qualities of Kombucha are already known in literature [16] and further noteworthy data could be discovered revealing inherent qualities of by-products-based broths aimed for MC culture. According to these studies, the use of diverse agricultural resources for MC production could emphasize its local origin and belonging through specialized applications.

By recognizing MC's potential and aiming to push forward its investigation and potential application, this paper presents the development of a bioreactor module called the 'InnoCell Bioreactor' (IB) as a self-produced unit enabling enhanced MC production and yield. The IB is an outcome of the interdisciplinary project InnoCell exploring the (g)local potential of Microbial Cellulose, its production and applications. The project supports knowledge democratization as it openly and transparently shares all the accumulated knowledge through an online platform. This article contextualizes the project by framing Biodesign as an emergent field with a focus on the design of new, sustainable materials that are 'grown' with the aid of existing organisms. It demonstrates how cross fertilization among disciplines supports the development of open-source tools providing optimal conditions for microbial processes making use of agri-food waste. A comparison is made among MC production methods, identifying the 'rotating disk bioreactor' as the most efficient one, and the main principles behind the IB function. Furthermore, the IB is designed as a 'do it yourself' module that could be scaled up or down according to need and technological availability. A following section highlights the role of the open-source platform in disseminating the instructions and the fermentation protocols, ensuring the IB's proper construction, use and maintenance. 'Future perspectives' discusses how improvements in the possible automatization of the IB could further optimize the monitoring and efficiency of the process. Eventually, emphasis is given to further speculation and system thinking towards production models strongly related to (g)local production systems and areas. In the conclusion the importance of the democratization of knowledge through open-source practices is stressed, expanding the act of growing from materials to networks of knowledge.

2 Bio-, Material-Design and InnoCell

Biodesign [17] is an emerging field in design also fostering sustainable materials development through the aid of -often integrated- living organisms (like bacteria, algae, fungi and hybrid cultures) in their processing and production. This approach sees microorganisms as co-workers of humans [18] that cultivate and 'grow' materials. Besides, material design is a practice in which designers identify underused resources within artificial production or natural environments [19]. With those, they make new circular materials while envisioning and creating sustainable material scenarios with beneficial social and environmental impacts. These two disciplines have many contact points and are often integrated. However, in order to obtain substances with specific characteristics, designers create new tools and optimize existing methods bridging scientific findings, industrial capabilities and environmental needs. The need for building efficient systems aimed at 'growing materials' is facilitated by today's digital fabrication and numerical control technologies which are distributed and enable efficient open-source knowledge transfer and applications. By highlighting the importance of open-source tools and self-made equipment in Biodesign, the InnoCell project explores the (g)local potential of Microbial Cellulose, its production and applications. Originating from a bachelor thesis project envisioning MC as a sustainable alternative for packaging [20] it furthermore explores a more local and distributed production of food products and (edible) materials. 'What if we made trash that feeds the environment rather than contaminates it?' [21] This scenario is supported by MC's valuable properties, local crafting potential and its inherent compostability. InnoCell, is a project led by a design team and a food-technology team, and partners with international stakeholders. The research takes place in the South Tyrol region which is renowned for its apple monocultures (12% of European production) [22] and develops scenarios proposing circular cycles by using apple-related waste to feed SCOBY cultures. This practice enhances the value of food-production byproducts fostering the development of more circular food and material production [23]. Locally manufactured MC novel food and non-food products could have considerable potential in future business perspectives, regional identity, its value creation and retention, management of resources and overall positive environmental impact. This production principle could be eventually applied to diverse areas around the world encouraging (g)local resilience practices. InnoCell shows how interdisciplinary grounds can become fruitful soils generating innovative scenarios. Through tangible and intangible tools and methods, scientific findings see potential applications and translation into industrial production dynamics proposing sustainable alternatives. Two important aspects of the project are the development of an open-source system for enhanced MC production: the InnoCell Bioreactor (IB) and an optimized recipe for apple-scraps-based broth for SCOBY fermentation.

3 MC Production Methods

Commonly used current systems in Kombucha drink and Nata de Coco industrial production are based on a MC fermentation method called static culture that uses tanks or trays. This procedure starts with the preparation of the liquid medium, which is poured in the meant container. An amount of SCOBY is immersed inside, and a breathable cloth or cover is put on the container to protect the culture from contamination. The culture is kept in static conditions (possibly supported by a system to control the temperature) for a period of 7 to 21 days - for the fermented beverage. At the end of the process a generated MC biofilm floats on top of the liquid, usually covering the complete surface. While being a very simple method to be reproduced, static culture used for MC production has its shortcomings: it is highly laborious to ensure a proper production rate, it provides a low efficiency concerning time and generated yield [24] and it does not enable easy control and adjustment of the culture during fermentation [25] as the MC membranes tend to cover the complete liquid/container surface. As it seems, MC is currently not existing as a raw material in the market, but SCOBY fermentation starters are highly available. However, startups, emerging companies and research institutes [26–29] are investigating and optimizing current methods and enhanced processes to produce MC-based products. With the same purposes, designers have been exploring MC production within the 'growing-design' [30] and digital bio-fabrication fields [31]. Current technologies with their accessibility and availability support designers in creating close relationships with machines and systems, promoting and spreading self-production [32].

Diverse techniques and machines to obtain MC biofilms and three-dimensional shapes [33–37] were developed but stayed eventually on a conceptual/proof-of-concept stage. However, a critical gap is present between home-brewing, experimental procedures and scaled-up production which brings anyone wishing to venture into MC experimentation to rely on DIY methods and often limited resources. Other existing processes which provide more efficient MC production are stirred and agitated cultures, rotating disk bioreactor, rotary biofilm contactor, spin filter-equipped bioreactor, reactor with a silicone biofilm [8, 11, 38]. According to Bungay et al. [11], the technique that appears to have the most effective time-yield ratio is rotating disk bioreactor (RDB). This system is characterized by a rotating shaft with perforated disks which serve as gripping elements for MC. The shaft is positioned partially immersed into a tank aimed to contain the liquid medium and the SCOBY. A motor performs a constant and smooth orbital movement which promotes an enhanced oxygenation into the culture. Over a period of 14–21 days MC thickens on both sides of the disks providing a remarkably higher yield in comparison to static culture thanks to surface optimization [39]. Indeed, a comparative study showed that an RDB system yielded 95% more mass than static fermentation and 31% more than shaken culture [38]. An aspect that needs to be considered is that RDB-produced MC has a higher water retention, and the studies refer to wet mass rather than dry mass.

Besides, another advantage is that as the biofilms do not grow directly on the liquid but on the disks so, controlling and adjusting the temperature, acidity (PH), sugar content (Brix) is practical and efficient. Moreover, the RDB is proven to be a space optimization production module, opening further industrialization possibilities and high-volume production.

4 Developing the InnoCell Bioreactor

The InnoCell Bioractor (IB) is based on scientific literature findings [11, 24, 25] and an expired patent [40]. It was developed for achieving optimal production and to be easily reproduced with distributed means available in small workshops, Fablabs, etc. Further on, its direct dissemination would follow through a dedicated online platform and would consist of a complete materials and components overview, their production and the IB maintenance instructions. All is aiming towards an optimized knowledge transfer and its democratization facilitating enhanced research. The development phase consists of iterative cycles of prototyping and testing that led to the final version of IB. In this phase, since the main goal is to create an open-source machine, digital fabrication techniques and easy to access components are used. A first 16l prototype was developed for testing the perforated disk patterns. A geared motor with encoder (12 V/28 RPM/80 kg) and a speed controller (5 V–30 V 6 A 150 W) enabled the identification of the ideal mechanical parameters for MC growth. The liquid medium preparation protocol and fermentation control were further-on iteratively tested by the project partners of the Food Technology Lab. A following 25l version (Fig. 1) was developed in order to produce bigger amounts of SCOBY. The IB, while having the same configuration of a rotating disk bioreactor, embeds further improvements and differences. The final version is assembled with components made through the aid of digital fabrication tools (3D printing, laser cutting) and a geared motor (52 MM, 12 MM, 6–12 VDC, 488:1) which is constantly turning; rpm change according to nourishing liquid ranging from 8,5 (apple) to 11 (tea). The design choices of the IB are strictly functional. Predominant materials are acrylic and polycarbonate because of microbial suitability and to simplify the checking of the MC culture and growth from the outside. Two removable external surfaces have disassemblable bearings and 3D printed holding structures which ensure a smooth rotation of the shaft positioned among them. The shaft has two inox holders at its ends which are inserted through the bearings. An additional central bearing placed on a support contributes to better distribute the weight of the shaft. The half cylinder shape of the tank optimizes the inner volume by following the profile of the twenty-eight disks that have a diameter of 25 cm. They are mounted on a square-profiled polycarbonate shaft, separated with 3D printed spacers and fixed with 3D printed stoppers. A specific pattern of holes, together with a surface treatment optimizes the growth of MC on the disks: a recent cycle generated wet MC mass per disk with an average of 500 g. per disk, reaching a total yield of 13,5 kg. Accessories like a removable cloth cover and a heating system (made of filter, universal aquarium pump, vertical liquid heater, tubes and a metal holder) were also designed to retain a constant temperature optimizing the fermentation conditions. In particular, the heating system creates a circulation of the liquid medium inside the tank which maintains the homogeneity of the culture.

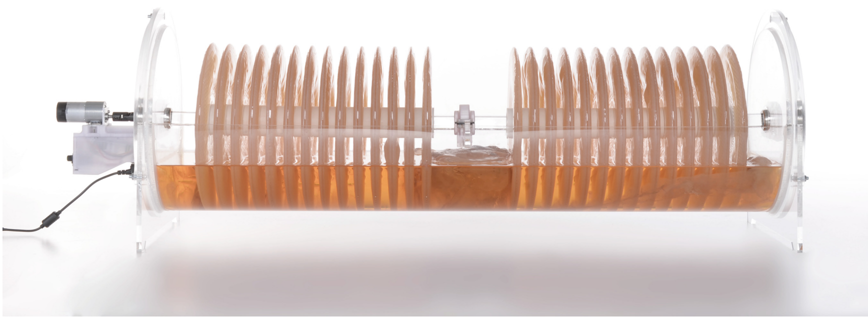

Fig. 1. 25l prototype (*heating and covering systems are not shown*)

5 Open Source

With the current design as an alternative to static culture production, the aim of the IB is to support anyone interested in venturing into MC through a more advanced production system. Instructions to build, use and maintain the IB will be disseminated through an online open-source platform currently under development. This means of knowledge transfer would possibly raise another dimension in the action of ‘growing’ by providing advanced tools to turn mere material tinkering into a more reliable and controllable food and non-food production possibilities. The concept of growth relates not only to the extension of production practices but also to ‘growing’ networks of knowledge. This principle is following a broader scope related to social sustainability, which is achieved when open knowledge makes sustainable development accessible by anyone. Therefore, an open online platform would serve as a dissemination tool to reach communities and individuals and foster further related research around the globe.

6 Future Perspectives

The current version of IB is a valuable prototype for further advanced iterations and a base for future scale-up and down. The knowledge and developed protocols are just as much suitable for both, industrial and more experimental scopes. Further evolution of the bioreactor could regard the automatization and monitoring of the process. These enhancements would considerably reduce the manual labor which is currently required throughout the cycle. Another aspect for future follow-up is the development of customized SCOBY cultures and optimized broth recipes related to diverse single resources recycled from agri-food production. Thus, this would optimize further-on the MC production and yield while potentially adapting it to stakeholders’ needs and food/non-food applications.

Systemic thinking [41] is fundamental in design practice to envision and propose meaningful products and production alternatives. With the current design, the IB is a highly effective, space-efficient module enabling high volume production. The module could aid anyone who is willing to venture into MC experimentation and production. The current module logic enables human-scale handling and management in ‘semi-handcrafting dimension’ [42]. Moreover, its integration in diverse systemic models could take place, not only MC production could be in-housed but specialized facilities could foster the creation of distributed systems. Speculative design scenarios developed within the InnoCell project envisioning the possible integration of MC manufacturing in current production cycles, aim at the creation of more resilient and connected communities [43]. Indeed, the IB can contribute to connecting food and non-food productions through MC fermentation. Indeed, benefits of the implementation of IB modules in the facilities or infrastructures of local producers (of apple products or derived from other fruit and vegetable sources) would regard the further utilization of byproducts generating new profitable foods or material-related profitable streams.

7 Conclusion

Microbial cellulose is recognized as a valuable edible and non-edible substance with promising potential for envisioning sustainable product solutions and new local production scenarios. Despite these favourable perspectives, it is observed that there is little accessibility to MC mass amounts and related R&D practices. By reacting on problematic aspects related to the most common MC production method namely static culture, the InnoCell project developed a bioreactor (IB) based on established scientific studies. The principle of rotating disk bioreactor was developed into a reproducible module that is open-source. This bioreactor can play a valuable role in future production and consumption perspectives related to food and non-food production realities. Indeed, the implementation of IB modules in the facilities or infrastructures of local producers could generate new profitable streams while applying a more circular approach towards byproducts.

All the information concerning the physical building and maintenance of the IB would be disseminated on an online platform. Moreover, protocols for optimized cultivation, applications and system implementation of apple-based MC are other key elements in the project's knowledge transfer, supporting further on (g)local MC research and production. In this way, the meaning of 'growing' would shift from alternative production practices to growing networks of knowledge. Through an interdisciplinary approach bringing together the design world with food-technology, the democratization of MC production knowledge and technologies would foster systemic sustainable alternatives. This concept is translated in the practice of fermenting underused resources to produce valuable and functional MC foods and materials with peculiar qualities.

References

1. Kataja, K., Kääriäinen, P.: Designing cellulose for the future: design-driven value chains in the world of cellulose (DWoC) 2013–2018. Final project report (2018)
2. Betlej, I., Zakaria, S., Krajewski, K., Boruszewski, P.J.: Bacterial cellulose - properties and its potential application. Sains Malaysiana **50**(2), 493–505 (2021)
3. Piadozo, M.E.S.: Nata de coco industry in the Philippines. In: Bacterial Nanocellulose: From Biotechnology to Bio-Economy, pp. 215–229 (2016)
4. Phisalaphong, M., et al.: Nata de coco Industry in Vietnam, Thailand, and Indonesia. In: Bacterial Nanocellulose, pp. 231–236 (2016)
5. Shi, Z., Zhang, Y., Phillips, G.O., Yang, G.: Utilization of bacterial cellulose in food. Food Hydrocolloids **35**, 539–554 (2014)
6. Azeredo, H., Barud, H.S., Farinas, C.S., Vasconcellos, V.M., Claro, A.M.: Bacterial cellulose as a raw material for food and food materials packaging applications. Front. Sustain. Food Syst. **3**, 7 (2019)
7. Revin, V., Liyaskina, E., Nazarkina, M., Bogatyreva, A., Shchankin, M.: Cost-effective production of bacterial cellulose using acidic food industry by-products. Braz. J. Microbiol. **49**, 151–159 (2018)
8. Chawla, P., Bajaj, I., Survase, S., Singhal, R.S.: Fermentative production and applications of microbial cellulose. Food Technol. Biotechnol. **47**(2), 107–124 (2009)
9. Czaja, W., Romanovicz, D., Brown, Jr.: Structural investigations of microbial cellulose produced in stationary and agitated culture. Cellulose **11**, 403–411 (2004)
10. Costa, A.F.S., Rocha, M.A.V., Sarubbo, L.A.: Bacterial cellulose: an ecofriendly biotextile. Int. J. Textile Fashion Technol. **7**, 11–26 (2017)
11. Bungay, R.H., Serafica, G., Mormino, R.: Environmental implications of microbial cellulose. Global Environ. Biotechnol. **66**, 691–701 (1997)
12. Mohammadshirazi, A., Bagheri Kalhor, E.: Energy and cost analyses of kombucha beverage production. Renew. Sustain. Energy Rev. **55**, 668–673 (2016)

13. Fan, X., et al.: Production of nano bacterial cellulose from beverage industrial waste of citrus peel and pomace using Komagataeibacter xylinus. Carbohyd. Polym. **151**, 1068–1072 (2016)
14. Llorach, P.: Circular Design and Circular Material Design in MaDe Book. Material Designers (2021). http://materialdesigners.org/book. Accessed 11 June 2021
15. Cohen, N., Sicher, E., Ugur Yavuz, S.: From agricultural waste to microbial growth and (g)local resilience. In: Senses and Sensibility 2019 Conference - Lost in (G)localization, Lisbon, Portugal, 26th–29th November 2019 (Unpublished manuscript, delivered 21/05/08)
16. Vitas, J., Popović, L., Cakarevic, J., Malbaša, R., Vukmanović, S.: In vitro assessment of bioaccessibility of the antioxidant activity of kombucha beverages after gastric and intestinal digestion. Food Feed Res. **47**(1), 33–42 (2020)
17. Myers, W.: Bio Design: Nature, Science Creativity. Thames & Hudson Ltd, New York (2012)
18. Collet, C.: Grow made textiles. In: Proceedings of Alive. Active. Adaptive, Delft University of Technology International Conference on Experiential Knowledge and Emerging Materials, pp. 24–37. TU Delft Open, Delft, 19–20 June 2017
19. Iles, J.: Expert interview in MaDe Book (2021). http://materialdesigners.org/book. Accessed 11 June 2021
20. Sicher, E.: BAThesis: from peel to peel-an experimental design approach for packaging. UNIBZ, Bozen-Bolzano (2017). https://ubz-primo.hosted.exlibris-group.com/permalink/f/tb3h4b/39UBZ_ALMA_DS21151949370001241. Accessed 11 June 2021
21. Valanidas, M.: The Breakup: Microbes + Bioplastics. Biodesigned (7) (2021)
22. ASTAT: 2015 Statistisches Jahrbuch für Südtirol (2015). http://astat.provin-cia.bz.it/downloads/Jahrbuch_2015.pdf. Accessed 11 June 2021
23. Guasch Sastre, C.: How Materials can Shape our Future in MaDe Book (2021). http://ma-terialdesigners.org/Book/. Accessed 22 Mar 2021
24. Pa'e, N.: Rotary discs reactor for enhanced production of microbial cellulose, Master Degree thesis, Faculty of Chemical Engineering, Universiti Teknologi Malaysia, Skudai, Johor (2009)
25. Pokalwar, S.U., Mishra, M.K., Manwar, A.V.: Production of cellulose by gluconacetobacter sp. Recent Res. Sci. Technol. **2**(7), 14–19 (2010)
26. MakeGrowLab: Scoby Packaging (2019). https://www.makegrowlab.com/scoby-packaging. Accessed 11 June 2021
27. ScobyTec (2019). http://www.scobytec.com/. Accessed 11 June 2021
28. Nanollose (2018). https://nanollose.com/. Accessed 11 June 2021
29. Bowil Biotech: (2021). https://bowil.pl/en/bowil-biotech-en/. Accessed 11 June 2021
30. Ciuffi, V.: Growing Design. Abitare **531**, 110–111 (2013)
31. Camere, S., Karana, E.: Growing materials for product design. In: Proceedings of the International Conference of the DRS Special Interest Group on Experiential Knowledge and Emerging Materials, 101–115. Delft University of Technology, Delft (2017)
32. Diez, T., Posada, A.: The fab and the smart city. The use of machines and tech-nology for the city production by its citizens'. In: Proceedings of the 7th TEI-New York, pp. 447–454. ACM Press, New York (2013)
33. Schwabe, S.: Growing a Roll (2012). http://www.stschwabe.com. Accessed 11 June 2021
34. Schwabe, S.: The Kernel of Chimaera. [Graduation Project]. RCA (2012). http://www.stschwabe.com. Accessed 11 June 2021
35. Schwabe, S., Huelsen, J.: Xylinum Cones Programming (2014). http://www.stschwabe.com. Accessed 30 Mar 2021
36. Gombosova, Z.: The Invisibile Resources (2014). https://vimeo.com/99483048. Accessed 11 June 2021
37. Dunne, A., Raby, F.: Bioliberals. United Micro Kingdoms (2013). http://unitedmicrokingdoms.org/bioliberals/. Accessed 11 June 2021

38. Zahan, K., Fadhrullah, M., Pa'e, N., Ng, C., Muhamad, I.: Designing economical production of microbial cellulose from waste using modified bioreactor. In: Proceedings of the ICPE 2010. Association for Computing Machinery, New York (2014)
39. Pajuelo, M., Hogg, T., Bungay, H., Vasconcelos, I.: Lowering costs for microbial cellulose (1997)
40. Bungay, H.R., Serafica, G.C.: US5955326A, United States (1995). https://pa-tents.google.com/patent/US5955326A/en. Accessed 11 June 2021
41. Meadows, D.H.: Thinking in Systems. Chelsea Green Publishing, Vermont (2015)
42. Parisi, S., Rognoli, V., Ayala Garcia, C.: Designing materials experiences through passing of time: material driven design method applied to mycelium-based composites. In: Proceedings of the 10th International Conference on Design and Emotion, Amsterdam, The Netherlands, pp. 239–255 (2016)
43. Manzini, E., M'Rithaa, M.K.: Distributed systems and cosmopolitan localism: an emerging design scenario for resilient societies. Sustain. Dev. **24**(5), 275–280 (2016)

Biodegradable Fibre-Based Composites as Alternative Materials for Sustainable Packaging Design

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Abstract. In recent times we have seen an emerging growth of petroleum-based materials in the packaging sector. The overuse of petroleum materials poses challenges to environmental sustainability due to its unplanned disposal at the end of its life. Plastic manufacturing is energy-intensive as it has a significant share in energy consumption. It also emits greenhouse gases like carbon dioxide, which harm the environment and atmosphere to some extent. They also contribute heavily to global warming by trapping carbon dioxide. Such problems can be addressed if biodegradable materials from renewable resources are used for packaging. In recently reported research, renewable and biodegradable materials have drawn much attention in the packaging domain due to their eco-friendly nature. For sustainable packaging, the material should be bio-based, and its constituents should be biodegradable. Sustainable textile materials have the potential to satisfy both conditions. Apart from environmental benefits, bio-based textile materials can be economically advantageous in packaging applications. This paper focuses on reviewing prior work done to identify sustainable packaging materials based on biodegradable fiber composites. It also considers studying the characteristics of various biodegradable textile materials and their potential usage in sustainable packaging design.

Keywords: Textile material · Packaging · Environmental sustainability

1 Introduction

Packaging is essential for the preservation and transportation, and presentation of various products. Its structural design should be robust to prevent any damage to the product during logistics or storage. Additionally, it should also be bearing information and aesthetically pleasing for the consumer to drive interest in the product [1]. Packaging can be categorized into primary, secondary, and tertiary, depending on its intended use. Primary packaging is one that comes in direct contact with the product, and it can be removed from the product before use. The secondary packaging protects the product physically, whereas tertiary packaging ensures product safety during storage and logistics [1]. Based on the type of material used, packaging may further be categorized as flexible, rigid, glass, paper, and others.

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Rigid packaging is used to pack products like milk, laundry detergents, toothpaste, shampoos, etc. It is usually expensive than other forms of packaging and uses strong materials like plastics and metals. The majority of these packages are made up of plastics like polyethylene (PE) and polypropylene (PP) which have a substantially large carbon footprint. Plastic packaging materials are highly environmentally unsustainable and impact the earth's environment, on which we rely. Most plastic waste is transported to landfills or disposed of in the environment. Only 9% of the 9.2 billion tonnes of plastic material that is produced is recycled properly. Because plastic is not biodegradable, every single piece of plastic ever made is still on the planet [2]. Plastic that is dumped or washed into the seas is eaten by marine organisms. Plastic pollution endangers biodiversity, disrupts environments, and endangers human health. Reduced plastic packaging production would reduce the risk of such harm. Even so, waste plastic disposed of in landfills is eventually incinerated to make way for new waste. Toxic pollutants and irritants are released into the air as plastic is burned. The time is now ripe for finding alternatives to conventionally used packaging materials for a sustainable future. Design and development of rigid packages made of sustainable materials need the hour as advocated by the sustainable packaging coalition. It states that the packaging should be "sourced responsibly, designed to be effective and safe throughout its life cycle, made entirely using renewable energy and once used, is recycled efficiently to provide a valuable resource for subsequent generations of packaging" [2]. Thus, there is a strong need to develop materials for rigid packaging which are sustainable.

2 Environmental Impacts of Rigid Packaging

Cups, cans, bottles, and corrugated boxes are examples of commonly occurring rigid packages. These packages are conventionally made from metal, plastic, paper, or glass, depending upon the product it is protecting. Among these, plastic is primarily used in majority of applications because of its superior chemical and mechanical properties. [3]. In 2017, the rigid packaging market globally was valued at an approximate cost of USD 504.64 billion. It is further expected to assume a value of USD 802.43 billion by the end of 2024, growing at an approximate CAGR of around 6.85% [4]. This tremendous market potential is primarily catered by plastic materials. Rigid packs which keep our milk fresh or ensure that our laundry detergent does not leak are made of polyethylene (PE), a type of plastic. It has become a cornerstone for developing most rigid packs due to their commercial viability and suitable properties like toughness, stiffness, barrier, mouldability, and chemical resistance. Other widely used plastics in the rigid pack development are HDPE, LDPE, MDPE, PET, PVC, and PC. Plastic materials, as mentioned above, are not biodegradable. Their accumulation in landfills is an issue of concern for the governments. Apart from the biodegradability issue, these rigid pack fractions are complicated to recover. Moreover, the recovered fractions' recyclability is yet another bottleneck for its re-use as the requisite properties are severely impacted. This leads to downcycling as material properties are being degraded at every stage [5]. The above-mentioned issues can be solved by designing rigid packages with biodegradable and sustainable materials. The use of biodegradable and natural fibers as fillers in conventional plastic materials can somewhat increase biodegradability. However, the material needs to be 100% biodegradable to make significant progress in the field of sustainable packaging design [6]. When used alone or in the form of composites, Biodegradable fibers have tremendous potential to remove conventionally used plastics in the construction of rigid packages [7]. However, a thorough consideration needs to be made regarding the requisite properties required for constructing a stable and efficient rigid package.

3 Requisite Properties for the Development of Rigid Packages for Various Application

For a material to be used successfully in a rigid pack, several properties need to be quantified and evaluated. These properties are essential for delivering the required performance of the packaging. The properties of packaging may vary depending on the application. The required properties of packaging materials for a specific application are as follows.

3.1 Food Packaging

Proper selection of appropriate packaging materials can preserve the shelf-life, quality, and freshness of the food. The primary function of the food package is to protect food from contamination. Migration is an important property in food packaging. Migration of the chemical compound from packaging into food can significantly change taste and flavour and cause health problems [8]. Thermal properties such as melting temperature (Tm), glass transition temperature (Tg), crystallization temperature, enthalpy, heat deformation temperature (HDT), and Chemical resistance also play an important role in protecting the food from the environment. Mechanical properties such as elasticity, coefficient of fraction, modulus, and Poison's ratio are important to protect the food from physical damage.

3.2 Electronics Packaging

Polymer composites have several advantages over the conventional materials used in the electronic packaging sector, such as lightweight, easy processability, and a high degree of protection from the environment. Based on our needs, we can engineer the required properties of the composite materials [9]. Electrical properties of the materials play an important role in the electronics packaging, such as dielectric constant, surface resistance of the material, dielectric strength, loss tangent, arc resistance, and volumetric resistivity. Electronic packaging materials can experience temperature variation, rate of change in temperature, thermal shocks during operation, manufacturing, storage, and transportation. So, thermomechanical and thermal properties such as Tg of polymer materials, deflection temperature, thermal conductivity, and coefficient of thermal expansion are the key parameters during the selection of electronic packaging material [10]. Mechanical properties affect the packaging material's ability to sustain shock, thermomechanical stress, vibration during manufacturing, storage, and transportation. Important mechanical properties in electronics packaging are tensile strength, modulus of elasticity, Poisson's ratio, and fracture toughness. Water absorption, corrosion resistance, and flammability are key parameters to survive during handling and operative environment.

3.3 General Packaging

Some common properties are required for packaging to sustain during processing, storage, transportation, and manufacturing. Mechanical properties of material tell us about its behaviour under loads during various manufacturing operations. The selected material should have mechanical strength enough to sustain transportation, package handling, and storage processes. The packaging material must withstand heat to which it may be subjected during processes including sterilization. It's essential to understand packaging materials' thermal properties. Further, the glass transition temperature, along with the melting temperature of a material influences the mechanical and thermal properties of the package. Glass transition temperature of packaging materials plays an important role during stored in a sub-freezing temperature. The development of rigid packs, the physical characteristics like water absorption, mass, humidity content, and width, must be evaluated. UV absorbency is also a desirable material property.

4 Biodegradable Fibres Based Composites

Biodegradable fiber-based composites traditionally consist of a biopolymer as a matrix phase and the biodegradable fiber as the reinforcement. Biopolymers can be made in a number of ways, including directly from natural sources such as proteins and polysaccharides or by polymerizing biomass-derived monomers, such as PLA derived from lactic acid. Microorganisms also produce biopolymers like polyhydroxyalkanoate (PHA) [11]. The following matrices and reinforcements can be used to make sustainable rigid packages.

4.1 Matrix Phase

Poly (lactic) Acid (PLA). As a biodegradable polymer for packaging, poly (lactic) acid (PLA) has received a substantial amount of attention because it is made from renewable resources. Various factors, like high amount of availability of PLA, environmental sustainability in packaging, high cost of petroleum-based plastics, have promoted the manufacturing of PLA-based composites that can act as viable alternatives to conventional packaging materials [12]. PLA is a suitable replacement for packaging material due to its excellent transparency, mechanical properties, biodegradability, oil and fat protection, and reusable properties. However, PLA also has some drawbacks, such as a lesser HDT, low stability for thermal properties, lesser strength of impact medium gas barrier attributes, low viscosity, brittleness, high price, and low resistance to solvents. So, these limitations can be overcome by adding fiber with PLA polymer-based composites.

Polyhydroxyalkanoate (PHA). Polyhydroxyalkanoates are 100% biodegradable microbial polyester with thermoplastic properties. A large variety of microorganisms can produce through sugar fermentation under nutrient stress [13]. Composites made of PHA-based matrices be used in single or one-time-use plastic, where biodegradability of PHA in compost, marine water, and soil is a significant benefit [14]. PHA polymers have good thermal and UV light resistance properties, and some industrial manufactures, PHAs, are used for food packaging. In the production of PHA-based packaging, coatings, and sanitary items, some market penetration has been achieved. It has excellent processability. Brittleness, high cost, and poor barrier properties can be overcome by the addition of fibers, fillers, and modifiers [15].

Cellulose and Derivatives. Cellulose polymers are made from plant material and are made up of-D-glucose subunits. Because cellulose is poorly soluble in water in its natural state, it is an unsuitable packaging material [16]. To become soluble in water, cellulose can be surface modified, coated, plasticized, or blended. Films and composites can be made from Nanofibers [17]. Nanofibers incorporated into a matrix (polymer-based) can surely improve the property of the moisture barrier without changing the biodegradability [17].

Polysaccharide and Starch. Chitin is a polysaccharide that is found in abundance in nature. It is ranked second in abundancy among organic compounds on the planet, behind cellulose. Chitosan is prepared from a repeating unit of 1, 4 linked 2-deoxy-2-amino glucose. Casting from an aqueous solution can produce hard and flexible chitosan films with good oxygen barriers. The lack of lower water vapor barrier properties and long-term stability of chitosan films are their demerits. Chitosan films have applications in keeping food safe from fungi and to change the environment of fresh fruits [18]. Biopolymer Starch is made by plants during photosynthesis within plant cells. Starch is found in granules with both amorphous and crystalline regions. Amylase and amylopectin are two homopolymers found in starch. Potatoes are one of the most commonly used commercial starches; other sources include corn, wheat, rice, and tapioca.

Proteins. Proteins are the potential alternative materials for packaging applications [19]. THERMOWHEY [20] and WHEYLAYER [21] have already developed oxygen fence coverings built on whey protein. To strengthen barrier properties while retaining biodegradability, a whey protein film was added to biodegradable packaging film [22]. To enhance thermoformability, Whey protein isolate and plasticizers, which are bio-based or reactive additives, are used to make the whey-protein-based coatings [22].

Lipids and Waxes. Fats, fatty acids, and waxes are examples of hydrophobic lipids. Lipids provide a very good barrier against migration of moisture due to their non-polar regions [23]. The addition of additional biopolymers as coatings to the lipids, such as polysaccharides or proteins, results in improved mechanical properties. Aside from having higher moisture permeability than pure lipid coatings, blends have higher barrier properties [24].

4.2 Natural Textile Fibres as a Reinforced Materials

Naturals fibres are another potential material for use as packaging in our daily lives. Natural fibers are gaining popularity due to their low density, which allows them to give a better toughness and specific strength in composites for packaging materials [7]. Fibers have several advantages over synthetic fibers. These are decomposable, ecological, and surplus. They also have good mechanical properties, improve conditions for working, and also cause less abrasion to the components with which they interact. All of this can help save money [25]. Natural fibre composites have some drawbacks, such as properties like high moisture absorption, incompatibility of being associated with certain polymeric matrices, and poor wettability [1, 26]. Fibre-matrix adhesion is the most common issue with natural fibre-based composites. The natural fiber-reinforced polymer, which forms composites with poor adhesion between hydrophobic polymers and hydrophilic fibers, further can have lower mechanical properties. A strong bond formation between the matrix and the fibers, therefore, becomes critical. The natural fibre can be chemically and physically treated to improve the desired properties [26]. The use of renewable fibers will facilitate the development of composite materials for demanding food and pharmaceutical packaging applications. Bio-based content and biodegradability are therefore essential for single-use, short-life disposable packaging and consumer plastics [27]. As reinforcements or fillers, a variety of different fibers may be used. Natural fibres are classified into three groups based on their origin, as shown in Fig. 1.

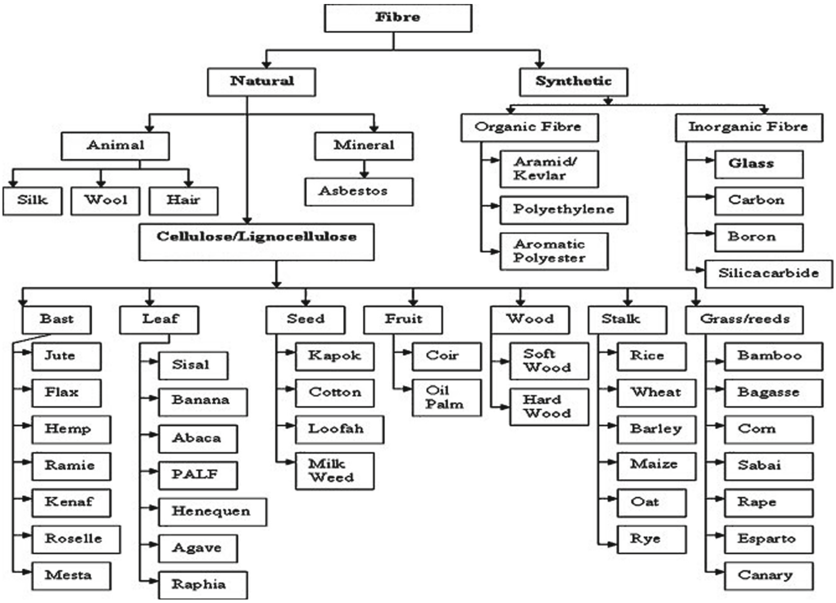

Fig. 1. Categories of natural fibres [28].

Mechanical and Physical Properties of Natural Fibres. Mechanical properties of natural fibers such as modulus, tensile strength, and elongation at breaks have been reported by various authors and reported in Table 1. Physical properties are also summarized in the same table.

4.3 Explanation for a Widely Used Natural Fibers in Packaging

Banana Fibre. Bananas are among the world's oldest cultivated plants, according to widespread belief. The Arabic word for banana is 'finger.' 300 species of banana exist

Table 1. Mechanical and physical properties of natural fibres [29–31].

Fibre	Density (Kg/m^3)	Diameter (μm)	Tensile strength (MPa)	Tensile modulus (GPa)	Percentage elongation
Jute	1460		393–800	10–30	1.5–1.8
Sisal	1450	50–300	530–640	9.4–20	3–7
Pineapple leaf	1440	20–80	609–700	23.7–30.3	0.8–16
Kenaf	1400	81	427–519	23.1–27.1	
Vakka	810	175–230	549	15.85	3.46
Abaca leaf	830	114–130	418–486	12–13.8	
Alfa	890		350	22	5.8
Nettle	1500	16–43	954–2234	59–119	1.5–6
Flax	1450		345–1500	27.6–80	12–3.2
Hemp	1200		550–900	70	1.6
Banana	1350	80–250	600	17.85	3.36
Coir	1250		131–220	4–6	15–30
Root	1150	100–650	157	6.2	3
Date palm	990		97–196	2.5–5.4	2–4.5
Bamboo	910	14	503	35.91	1.4
Talipot	890	200–700	143–263	9.3–13.3	2.7–5
Snake grass	887	45–250	278.82	9.71	2.87
Elephant grass	817	70–400	185	7.4	2.5
Petiole bark	690	250–650	185	15	2.1
Spatha	690	150–400	75.6	3.1	6
Palm	1030	400–490	377	2.75	13.71
Agave	1200	126–344			
Henequen	1200		430–570	11.1–16.3	3.7–5.9
Bagasse	1250	200–400	290	11	
Curaua	1400	170	157–729		5
Oil palm		150–500	80–248	0.5–3.2	17–25
Piassava			134–143	1.07–4.59	7.8–21.9
PALF		20–80	180–1627	1.44–82.5	1.6–14.5
Ramie		20–80	400–1000	24.5–128	1.2–4.0
Isora			500–600		5–6

(*continued*)

Table 1. (*continued*)

Fibre	Density (Kg/m^3)	Diameter (μm)	Tensile strength (MPa)	Tensile modulus (GPa)	Percentage elongation
Cotton	1600		287–597	5.5–12.6	3–10
Ramie	1500		220–938	44–128	2–3
Rachis			74.26	2.31	13.5
Rachilla			61.36	2.34	8.1
Palmyrah			180–215	7.7–20	7–15
Date palm			97–196	2.5–5.4	2–4.5
Kapok			45–64	1.73–2.55	2–4
Okra			184–557.3	8.9–11.8	4–8

in the Musaceae family, but 20 varieties are consumed. It was investigated how to make green composites with banana fibre and soy protein as the matrix. Alkali-treated and untreated fibres were mixed into soy protein isolate (SPI) with varying amounts of glycerol (2250%) as a plasticizer in their study. The biodegradability test shows the composites are 100% biodegradable [32].

Jute Fibre. Jute and whole jute pulp have a high burst index, making them a preferred raw material for corrugated boards [33]. Jute-cotton blend, jute-kenaf, and jute Roselle Blend, Jute Ramie blend, Jute-Flax blend, Jute-Sunna Hemp, Jute-Abutilon Blend, Jute-Coconut Fibre, Jute-Sisal Blends, and Jute-Wool Blend were prepared were made, and superior properties were observed. These blends can be alternative options for sustainable packaging materials [34]. Eco-friendly nature of jute fibres saturated with Petit Verdot Red Grape Pomace Extract was projected as a new active food packaging substitute for this study.

Bamboo Fibre. One of the most underutilized natural resources in Southeast Asia is Bamboo, where it grows in abundance [35]. In terms of bamboo diversity, India is second only to China. The 58 bamboo varieties found in the North-Eastern States are a treasure trove of bamboo diversity. Ten million hectares of land are used for bamboo cultivation in India, accounting for nearly a third of its total forest area. Bamboo is produced at a rate of five million tonnes per year. Bamboo provides a living for approximately 8.6 million people. Bamboo has a market value of $4.4 billion in India [36].

Flax Fibre. Flax fibers are natural fibers and have potential for use in the packaging sector. The use of flax fiber in green composites has gained attention due to the increasing demand for developing eco-friendly packaging materials. Flax fibre reinforced green composites have good mechanical properties comparable to unsustainable materials. High humid conditions can degrade the mechanical properties of the flax fibres. Physical and mechanical modification processes and appropriate manufacturing methods can improve the mechanical properties of the flax composite. Recently, Poly (lactic acid)

(PLA) and short flax fibres based biodegradable composites were developed by extrusion process [37].

5 Recent Development in Biodegradable Composites for Packaging

Natural fibre composites have already begun to be used in traditional plastic packaging materials by a few companies. Composites made entirely of renewable resources can be used as packaging at the manufacturing level as eco-friendly friendly materials, which could replace conventionally available commodity plastics. They can be used in protective packaging as well as rigid packaging. These products will provide satisfactory service and, under certain composting conditions, will return to nature after its application is completed. Recently, an innovative and sustainable biodegradable composite was developed for tertiary packaging application. Composite was made of straw as reinforced material and biodegradable plastic as a matrix material [38].

5.1 Electronics Packaging

Non-food agricultural waste, as well as mycelium, are used in sustainable packaging. Mycelium, the mushroom's root structure, acts as a natural glue to hold everything together. This product is entirely compostable. When it comes into contact with moisture and soil microbes, it begins to biodegrade. Dell collaborated with Mushroom Packaging for Dell's servers to create high-performance, biodegradable packaging made of mycelium and hemp [39]. Dell was the first company to use bamboo packaging sourced from renewable resources. Bamboo resources are the ideal eco-friendly cushioning for select Dell laptops because of their incredible rate of renewal [40]. Digikey uses it as part of an effort to make more environmentally friendly electronics packaging. Bubble wrap can be replaced with Geami [41]. BenQ designed full molded pulp packaging for their projectors, making 100% recyclable packaging for electronics. The mobile box is made from raw bagasse, adding to the product's eco-friendly and natural feel [42].

5.2 Cosmetics Packaging

FS Korea uses wood-plastic composites for cosmetic packaging. To reduce the use of petroleum-based polymers, this substitute material has been used in their packaging designs. Containers for a perfume made from curauá fibre/wood flour composites have been developed. This new specialty compound meets the customer's desire to include natural components in the packaging to complement the all-natural ingredients [43].

5.3 Food Packaging and Liquid Packaging

A Bio-Based composite Development project (funded by EU) created a biodegradable plastic food packaging made of 75% PLA and up to 25% wood fibres. Cups made of bamboo fibre and PLA are available on the market. PHBV, a sustainable biopolymer made from cheese whey and micro-cellulose from almond shells, is used to make

YPACK's compostable packaging [44]. CFK packaging, a Canadian company, manufactures Earthcycle® packaging in Malaysia. Palm fibre is used to make Earthcycle pulp [45]. Vegan Bottle is a sugarcane fibre-based bottle that is 100% biodegradable, can hold liquids such as oil, beer, and even perfume [46]. Bacardi has collaborated with Danimer Scientific, a biodegradable product manufacturer, to manufacture a bottle made from natural oils derived from seeds such as palm, canola, and soy. After 18 months, without leaving any traces of microplastics, the plant polymer-based bottle will biodegrade [47]. Green Gen, based in France, hopes to be the first to market with a lightweight flax-based bottle. It's a bio-based alternative to glass, made from a flax fibre composite. Green Gen initially developed a "Zero-glass bottle" for the high-end wine market. The containers are appropriate for all industries that use glass, including alcoholic beverages and cosmetics [48].

6 Conclusion and Future Scope of Biodegradable Packaging Materials

Rigid packaging is rarely collected and recycled, so using sustainable compostable or environmentally biodegradable materials for rigid packaging is both a challenge and an opportunity for long-term sustainability. Natural fiber-based biocomposites have the potential to replace petroleum-based packaging material. Biocomposites are environmentally sustainable, but they have certain limitations, such as moisture barrier properties, thermal resistance, and mechanical properties. Few innovative bio-based and compostable natural fiber-based composites materials have already developed. They are suitable for rigid packaging, while others are in the works with very promising properties and prospects. It is essential to raise consumer and policy awareness to encourage the development of environmentally sustainable rigid packaging. This article will help those interested in developing natural fiber-based eco-friendly composite materials for the packaging application. It will also provide novel insight into the physical and mechanical properties of natural fiber for the development of bio-based composite.

References

1. Pickering, K. (ed.): Properties and Performance of Natural-Fibre Composites. Woodhead Publishing Limited, Cambridge (2008)
2. Packaging waste 101: the problem. https://supplychain.edf.org/resources/sustainability-101-packaging-waste-the-problem/. Accessed 22 Feb 2021
3. Rigid Packaging Market. https://www.persistencemarketresearch.com/market-research/rigid-packaging-market.asp. Accessed 12 Feb 2021
4. Rigid Packaging Market. https://www.zionmarketresearch.com/report/rigid-packaging-market. Accessed 28 Feb 2021
5. Cinelli, P., Coltelli, M.B., Signori, F., Morganti, P., Lazzeri, A.: Cosmetic packaging to save the environment: future perspectives. Cosmetics **6**(2), 26 (2019)
6. Ho, M.P., Lau, K.T., Wang, H., Hui, D.: Improvement on the properties of polylactic acid (PLA) using bamboo charcoal particles. Compos. B Eng. **81**, 14–25 (2015)

7. Ncube, L.K., Ude, A.U., Ogunmuyiwa, E.N., Zulkifli, R., Beas, I.N.: Environmental impact of food packaging materials: a review of contemporary development from conventional plastics to polylactic acid based materials. Materials **13**(21), 4994 (2020)
8. İçöz, A., Eker, B.: Selection of food packaging material. migration and its effects on food quality. In: 1st International Conference on Quality of Life, pp. 201–210. Center for Quality, Faculty of Engineering, University of Kragujevac (2016)
9. Wan, Y.J., Li, G., Yao, Y.M., Zeng, X.L., Zhu, P.L., Sun, R.: Recent advances in polymer-based electronic packaging materials. Compos. Commun. **19**, 154–167 (2020)
10. Pecht, M., Agarwal, R., McCluskey, F.P., Dishongh, T.J., Javadpour, S., Mahajan, R.: Electronic Packaging Materials and Their Properties. CRC Press, Boca Raton (2017)
11. Blackburn, R. (ed.): Sustainable Textiles: Life Cycle and Environmental Impact. Elsevier (2009)
12. Mukherjee, T., Kao, N.: PLA based biopolymer reinforced with natural fibre: a review. J. Polym. Environ. **19**(3), 714–725 (2011). https://doi.org/10.1007/s10924-011-0320-6
13. Philip, S., Keshavarz, T., Roy, I.: Polyhydroxyalkanoates: biodegradable polymers with a range of applications. J. Chem. Technol. Biotechnol. Int. Res. Process Environ. Clean Technol. **82**(3), 233–247 (2007)
14. Meereboer, K.W., Misra, M., Mohanty, A.K.: Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites. Green Chem. **22**(17), 5519–5558 (2020)
15. Endres, H.J., Siebert-Raths, A.: Engineering biopolymers. Eng. Biopolym **71148**, 3–15 (2011)
16. Hu, B.: Biopolymer-based lightweight materials for packaging applications. In: Lightweight Materials from Biopolymers and Biofibers, pp. 239–255 (2014)
17. Pandey, J.K., Kumar, A.P., Misra, M., Mohanty, A.K., Drzal, L.T., Palsingh, R.: Recent advances in biodegradable nanocomposites. J. Nanosci. Nanotechnol. **5**(4), 497–526 (2005)
18. Duan, C., et al.: Chitosan as a preservative for fruits and vegetables: a review on chemistry and antimicrobial properties. J. Bioresour. Bioprod. **4**(1), 11–21 (2019)
19. Calva-Estrada, S.J., Jiménez-Fernández, M., Lugo-Cervantes, E.: Protein-based films: advances in the development of biomaterials applicable to food packaging. Food Eng. Rev. **11**(2), 78–92 (2019). https://doi.org/10.1007/s12393-019-09189-w
20. Thermo Whey. http://thermowhey.eu/. Accessed 21 Feb 2021
21. Demonstration session of wheylayer2. http://www.wheylayer.eu/de/. Accessed 16 Feb 2021
22. Cinelli, P., et al.: Whey protein layer applied on biodegradable packaging film to improve barrier properties while maintaining biodegradability. Polym. Degrad. Stab. **108**, 151–157 (2014)
23. Morillon, V., Debeaufort, F., Blond, G., Capelle, M., Voilley, A.: Factors affecting the moisture permeability of lipid-based edible films: a review. Crit. Rev. Food Sci. Nutr. **42**(1), 67–89 (2002)
24. Bravin, B., Peressini, D., Sensidoni, A.: Development and application of polysaccharide–lipid edible coating to extend shelf-life of dry bakery products. J. Food Eng. **76**(3), 280–290 (2006)
25. Faruk, O., Bledzki, A.K., Fink, H.P., Sain, M.: Progress report on natural fiber reinforced composites. Macromol. Mater. Eng. **299**(1), 9–26 (2014)
26. El-Sabbagh, A.: Effect of coupling agent on natural fibre in natural fibre/polypropylene composites on mechanical and thermal behaviour. Compos. B Eng. **57**, 126–135 (2014)
27. Narayan, R.: Biobased and biodegradable polymer materials: rationale, drivers, and technology exemplars. In: ACS Symposium Series, vol. 939 (2006)
28. Nurul Fazita, M.R., et al.: Green composites made of bamboo fabric and poly (lactic) acid for packaging applications—a review. Materials **9**(6), 435 (2016)
29. Sathishkumar, T.P., Navaneethakrishnan, P., Shankar, S., Rajasekar, R., Rajini, N.: Characterization of natural fiber and composites–a review. J. Reinf. Plast. Compos. **32**(19), 1457–1476 (2013)

30. Büyükkaya, K., Güner, F.: Determination of static fracture toughness of nettle fibre (urtica dioica)/polymethyl-methacrylate composites using different fracture methods. Mechanics **26**(2), 95–102 (2020)
31. Mylsamy, K., Rajendran, I.: Investigation on physio-chemical and mechanical properties of raw and alkali-treated Agave Americana fiber. J. Reinf. Plast. Compos. **29**(19), 2925–2935 (2010)
32. Kumar, R., Choudhary, V., Mishra, S., Varma, I.: Banana fiber-reinforced biodegradable soy protein composites. Front. Chem. China **3**(3), 243–250 (2008). https://doi.org/10.1007/s11458-008-0069-1
33. Roy, A.K., Chattopadhyay, S.N.: Jute an alternative raw material for packaging paper. In: IPPTA, vol. 24, no. 3, pp. 121–124 (2012)
34. Basu, G., Roy, A.N.: Blending of jute with different natural fibres. J. Nat. Fibers **4**(4), 13–29 (2008)
35. Lobovikov, M., et al.: World Bamboo Resources: A Thematic Study Prepared in the Framework of the Global Forest Resources Assessment 2005 (No. 18). Food & Agriculture Organization (2007)
36. Greening India by planting bamboo. https://www.thehindubusinessline.com/opinion/greening-india-by-planting-bamboo-ep/article25009098.ece. Accessed 30 Apr 2021
37. Aliotta, L., Gigante, V., Coltelli, M.B., Cinelli, P., Lazzeri, A., Seggiani, M.: Thermo-mechanical properties of PLA/short flax fiber biocomposites. Appl. Sci. **9**(18), 3797 (2019)
38. Rossi, G., et al.: A new eco-friendly packaging material made of straw and bioplastic. J. Agric. Eng. **51**(4), 185–191 (2020)
39. Dell to use mushroom-based cushioning. https://www.packagingdigest.com/smart-packaging/dell-use-mushroom-based-cushioning. Accessed 30 Mar 2021
40. Bio-based resources. https://corporate.delltechnologies.com/en-us/social-impact/advancing-sustainability/sustainable-products-and-services/materials-use/bio-based-resources.htm. Accessed 03 Jan 2021
41. BenQ Projector Molded Pulp Packaging. https://ifworlddesignguide.com/entry/248456-benq-projector-molded-pulp-packaging. Accessed 12 Mar 2021
42. Electronic Box. http://www.pisourcing.com/ProductInfo.aspx?id=219&typeid=16. Accessed 12 Mar 2021
43. The new Eco range by FS Korea, featuring WPC elements. https://www.webpackaging.com/en/portals/fskoreaindustriesinc/assets/11010263/the-new-eco-range-by-fs-korea-featuring-wpc-elements/. Accessed 20 Apr 2021
44. Bioplastics News. https://bioplasticsnews.com/2020/06/12/ypack-biodegradable-food-packaging-shelf-life/. Accessed 16 Mar 2021
45. Bio-based food packaging in Sustainable Development. http://www.fao.org/forestry/45849-023667e93ce5f79f4df3c74688c2067cc.pdf. Accessed 15 Mar 2021
46. RESET Digital for good. https://en.reset.org/blog/introducing-first-biodegradable-bottle-made-sugar-cane-11212017. Accessed 22 Mar 2021
47. SPIRITS Business. https://www.thespiritsbusiness.com/2020/10/bacardi-unveils-biodegradable-bottles/. Accessed 29 Mar 2021
48. Flax fibre bottle challenges glass traditions. https://www.thepackhub.com/innovation-zone-snapshot-flax-fibre-bottle-23-sided-shoe-box-and-more/. Accessed 30 Mar 2021

Lay the Foundations for Building a Robust Eco-Design Methodology

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Abstract. This paper presents and discusses the possible theoretical bases of a comprehensive approach of robust eco-design to reduce the variations of the environmental impact of a product, compared to the baseline. The goal is to overcome the main limitations of contributions to the state of the art, i.e. the lack of a single approach to treat all possible causes, practical application and rigor in discussing the issues of environmental sustainability. The proposal is the intersection between eco-assessment, design theories and robust design. The eco-assessment provides the basis for an initial formulation of the environmental problems to be faced, which are correlated to the variation of the impacts. The design theories allow, through their ontology, to reformulate environmental problems in a more appropriate way to be addressed by the designer and at the same time provide, together with the robust design methods, suggestions to search the solutions. The analysis presented and the application proposal help to show the complexity and heterogeneity of the topic and reinforce the idea of introducing a systematic methodology to select the most appropriate method and favour its targeted use.

Keywords: Robust eco-design · Robust design · Design theories · Eco-design

1 Introduction and State of the Art

The variations of the environmental impacts of a product or a process compared to the esteemed value, because of a sudden and unforeseen phenomenon, can also be very consistent and cause very serious problems on the eco-system. Consider, for example, the consequences of accidents in nuclear power plants or oil tankers.

It cannot be said that approaches, theories, methods and tools have not been proposed to improve products by making them more resistant to failures, e.g. Robust Design, Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), etc.

However, their focus is not to manage problems from a point of view strictly connected with environmental sustainability, unlike the reduction of environmental impacts which is instead supported by different specific Eco-design approaches.

Most of the methodological proposals that explicitly refer to the reduction of the variability of environmental impacts are substantially modifications of the more general methods of failure investigation.

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Approaches dedicated to avoiding the environmental effects deriving from product failures are mainly based on FMEA (e.g. [1–3]), using it individually or within wider methodologies, such as Life Cycle Assessment and Lean Six Sigma. In them, the canonical modality of the FMEA is exploited to derive the failures, passing through the determination of the Failure Modes, which are typically obtained by brainstorming, starting from the list of product components or its functions. What changes, however, is the way in which the risk associated with certain failures is evaluated. Instead of using a purely numerical index, correlated to standardized severity factors for human health or for the realization of product requirements, in this case, the risk is assessed by using environmental impact indicators. Therefore, with problem solving activities, the possibility of occurrence of the most impacting failures is reduced or eliminated by improving the product. Some alternatives prefer other methods to the FMEA such as the FTA or the Analytical Hierarchy Process - AHP (e.g. [4]).

There are also other approaches that aim to reduce the variations in environmental impacts resulting from the influences of the external environment. Some of them provide suggestions obtained in an empirical way by analysing certain products (e.g. [5, 6]). Others based on the Resilience theory (e.g. [7, 8]) propose more qualitative and less specific suggestions. Still others considered Robust design (e.g. [9]), which can be considered the quantitative counterpart of the Resilience theory. Its main advantage in this field is the very broad analysis of many influencing factors that are also very different from each other and the analysis perspective extended to the entire life cycle of the product.

Finally, there are the approaches aiming to eliminate the environmental effects resulting from the misuse of the product caused by the user. This topic was particularly discussed in design theories and mainly concerns the design of the user-product interface (e.g. [10]) and the introduction of affordances [11], which are the qualities or properties of the product that define its possible uses or make clear how it can or should be used.

However, despite the many efforts spent and the many proposals, these methods still have some limitations.

- Robust design has been criticized for focusing mainly on the manufacturing phase and a certain difficulty at the application level, perceived above all by industry, due to the lack of pragmatism [9].
- In empirical approaches there is a strong relationship with a certain product, the surrounding conditions are rather stringent and the few environmental situations that have been tested make their results difficult to reuse and generalize.
- In general, the attention to environmental sustainability is rather marginal, often treated in an implicit, superficial, or totally neglected way. For these reasons, it is difficult for the designer to understand what to intervene on [12].
- Finally, in the literature there is no single approach to address all the possible causes of impact variations, but only some.

This paper discusses on a theoretical level how the integration of Eco-assessment, Design theories and Robust design should be integrated to build a structured methodology of robust eco-design, to reduce the variations of the environmental impacts, by overcoming the current limitations.

2 Proposal of Integration: Theoretical Discussion

From the analysis of the proposals at the state of the art, no problems arise with current methods such that they must be modified or replaced.

However, to face the problem of reducing the variations of the environmental impacts in a pragmatic and comprehensive way, it is necessary to guide the designer in choosing the right method to use and to provide rigorous environmental considerations to allow their more targeted use of the methods.

For this reason, any application proposal should work at the intersection between eco-design, design theories and robust design (see Fig. 1). In it, the eco-assessment should provide the basis for the selection of design or robust design methods as appropriate, and their solutions.

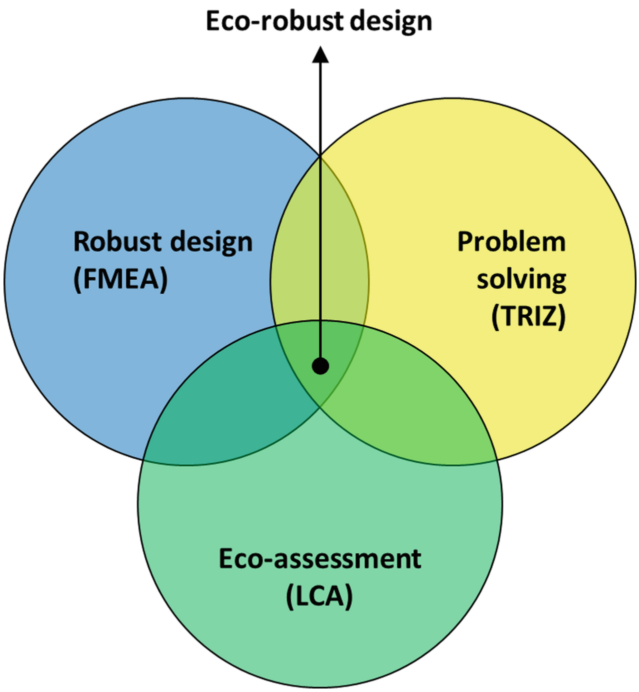

Fig. 1. The problem of the reduction of the variations of the environmental impacts should be solved considering eco-assessment, design theories and robust design.

Drawing contributions from each discipline, a three-step method for reducing variations in environmental impacts was developed:

1. Quantifying the environmental impact variations.
2. Defining what are the sources of impact, or the problems to be solved.
3. Solving the problems.

The following sections discuss the possible contributions that each discipline can bring to solve the problem of reducing the variability of the environmental impact of the product.

2.1 Quantifying the Environmental Impact Variations

The task of the eco-assessment could be to provide the initial criteria for selecting the right methodology to be applied according to the cause of variation in environmental impacts.

For this purpose, the organization of the Life Cycle Assessment (LCA) could be useful. It is unanimously considered one of the most useful for quantitatively evaluating the sustainability of the current technologies, to critically discuss the choices to implement during eco-design and to evaluate the environmental performances of the new developed technologies [13]. Furthermore, the LCA has already been used to show how the environmental impacts of a product can vary depending on the operating scenario and the different use modalities (e.g. [14, 15]).

To be able to express a sufficiently reliable estimate of its results, the LCA goes through several steps, which are regulated by the reference standards [16] and which may also be useful for classifying robust eco-design initial problems:

- The functional unit has the objective to reformulate and identify a reference unit to describe the standardized functioning modality of the product. When the product is used by a user, also ethnographic habits should be taken into account to properly identify the functional unit.
- The reference scenario is based on the definition of the system boundaries and it describe the standard condition of the working environment. It can include the description of the infrastructure, the climatic conditions, the geographical aspects.
- The inventory collects all the data about the environmental impacts arising from all the life cycle phases and they regard both the materials of the product and the energy consumptions.

Each of these steps can serve as a benchmark for identifying and solving the problems that cause the variations of the environmental impacts.

The problem of respecting the reference parameters of the functional unit, places us in front of the need to reduce the variability of the environmental impacts deriving from variations in the functioning of the product. Consequently, to solve this problem we should make sure that the product always behaves the same way, processing the inputs and obtaining the established outputs, throughout the operational life.

The second problem places us in front of the need to reduce the variability of the environmental impacts of the product following changes in the reference scenario. They can be different climatic characteristics (e.g. pressure, temperature, humidity), geographical (e.g. the type of route in which a car travels) or infrastructural (e.g. electricity mix).

Finally, the third problem concerns the reduction of the variability of the structural characteristics of the product, such as masses, geometries, and types of materials.

2.2 Defining the Sources of Impact

The object of this second step is to reformulate the variations of the environmental impacts in a more suitable manner to be faced during problem-solving activity. For this purpose, the simplified approach of FMEA-TRIZ proposed by [17] was considered.

The core of this approach is the determination of the failure modes, i.e. the modified elements of the system, due to external influences, causing the variations of the environmental impacts. For instance, a rod with a reduced diameter (failure mode) caused by corrosion (external influence) early breaks causing the reduction of its operative life (from which it derives the variation of the environmental impact).

ENV model from TRIZ theory is a useful tool to be adopted to determine the possible failure mode in the modified version proposed by the authors (see Table 1). According to this approach, the components of the technical system (Column 1 – "Element") are described through their parameters (Column 2 – "Name") and for each parameter, the effects deriving from an arbitrary variation of the parameters (Column 3 - Value) are determined (Column 4) and evaluated according to their risk occurrence by using the Risk Priority Number (Column 5 - RPN). In this table, a failure mode results from the conjunction of an Element, a Name, and a Value.

Table 1. ENV model used to determine the failure modes and their effects from [17].

Failure modes

Element	Name	Value (vs. design)	Effect	RPN
El. energy	Current intensity	Higher	Electrocution	20
		Lower	Engine and resistance fail	12
Max temp. allowed	Temperature	Higher	Overheating of hairdryer	14
		Lower	Useless shut down of hairdryer	10
	...	...	...	
Engine	Rotation speed	Higher	Overheating	18
			Mechanical failure	24
		Lower	Poor performance	8
		Absent	Hairdryer fails	12
	Noise	Higher	Acoustic discomfort	8
	Vibration	Higher	User's perceived value	8
	...	...	...	
Fan	Rotation speed	Higher	Increased noise	8
		Absent	Air is not moved	10
	...	...	...	

2.3 Solving the Problems

TRIZ method [18] is applied to solve the identified problems, by: (1) providing the ontological tools to reformulate the problems defined in Sect. 2.2, and (2) providing the tools to solve it.

TRIZ method can be defined at the same time as a heuristic method and a collection of tools to systematically solve a technical problem in a creative way, following a path divided into three main steps:

1. General problem formulation: starting from a specific problem, you gather all the information, and you reformulate it in an abstract way, using some of the tools of the theory (top model or small model, ENV model, Ideal Final Result). The final reformulation is in terms of contradictions or a kind of functional analysis called Su-Field model.
2. Concept/General solution definition: Contradictions and other problem models can be translated into conceptual solutions by means of TRIZ techniques (ARIZ, separation principles, contradiction matrix, 40 Inventive Principles, 76 Standard Solutions). In this way the designer works with a finite number of general suggestions.
3. Specific solutions definition: the designer must translate the conceptual identikit of a solution into a real and working solution by using resources already present in the product itself or in its environment.

The typical TRIZ path comprising the three described steps is presented in Fig. 2.

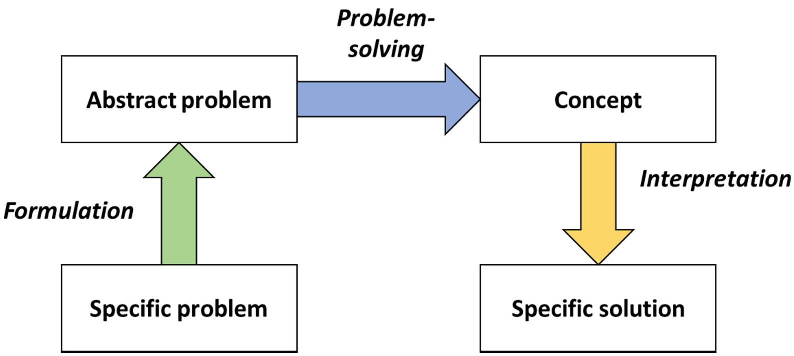

Fig. 2. Typical TRIZ path.

The reformulation of the initial problem, in TRIZ method is supported by the Minimal Technical System model. It is used to describe the Technical system and its functioning by only including a minimum number of ontological elements presented in Table 2.

By applying these definitions, it is possible to reformulate the initial problems in a more congenial way for their resolution. Then the reformulated problem can be approached by using the TRIZ path with its main tools (i.e. Step 2 and Step 3). The use of these tools cab be effectively able to solve the initial problems or to reduce the environmental impacts or their variations as qualitatively showed in in [19, 20] and [21]

Table 2. Some elements of TRIZ ontology.

Ontological elements	Definitions
Function	The action performed by the Technical system
Object	The entity over which the Technical system performs the Function
Product	The transformed Object after the Function has been performed
Tool	The part of the Technical system that is in direct contact with the Object during the performance of the Function. The contact can be mechanical, acoustical, thermal, chemical, electrical, magnetic, intermolecular, or biological
Other elements of the Technical system	• Supply: the part generating the energy • Transmission: the part transmitting the energy generated by the Supply to the Tool • Control: the part interacting with Supply, Transmission and Tool to regulate the execution of the Function on the Object
Resource	• Any substance, including waste, available in the Technical System or in the working environment • An energy reserve, free time, unoccupied space, information • Physical, chemical, geometric properties of the substances

and quantitatively demonstrated through the eco-assessment of the proposed solutions in [22].

2.4 Case Study

To demonstrate how can the approach be used, a case study about a compressed air dryer is proposed. This system is used where it is required to remove moisture from a continuous and massive flow of compressed air, typically in oil and gas applications or downstream of a compressor feeding an industrial plant. The main requirements are the quality of the function and the continuity of operation since the presence of moisture in the compressed air can cause serious problems of wear and reduced efficiency of the powered components. This system is installed after a compressor and it includes two column tanks placed in parallel containing the alumina. The two columns work in an alternating way: during phase 1, in one tank the compressed air is dried and in the other the alumina is hot regenerated, and vice versa during phase 2. To regenerate the alumina, it is heated with a stream of hot air that is drawn from the same flow rate of compressed air just produced by the compressor and heated by a heater. The hot, moist air exiting this tank is then dehumidified by means of a chiller with a condensate separator and combined with the main flow of compressed air before entering the drying column.

Figure 3 depicts a schematic representation of the functioning (one of the two phases) and CAD model of the considered Technical system.

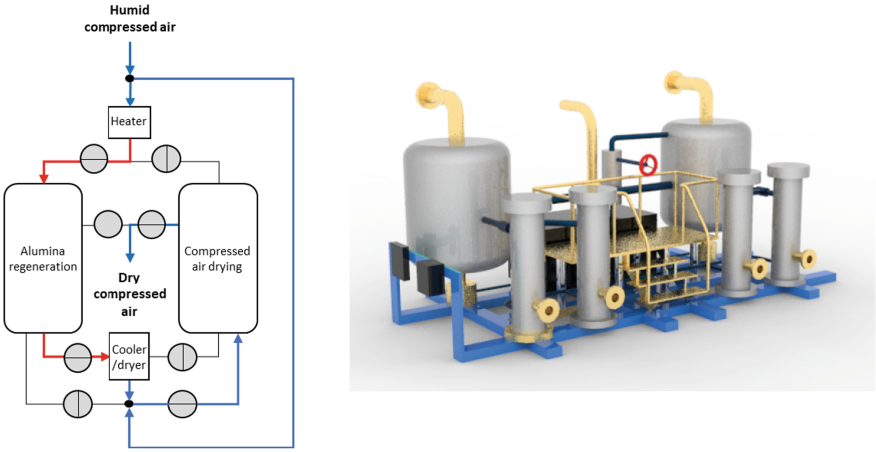

Fig. 3. Schematic representation of the functioning and CAD model of the Technical system.

One of the causes of the variation of the environmental impacts depends by the variation of the flow rate of air that is dehumidified. This flow is in fact one of the main parameters to be considered when defining the functional unit in a LCA study of this product. Consequently, the environmental problem to be faced is: "How can the effects of the variability of the technical system functioning be reduced?".

One of the most obvious strategy is to reason about the possible inefficiencies during dryer operation.

Reformulating the problem in order to identify the failure mode, we can state that there is a variability in the characteristics of the Product (i.e. the dried compressed air) compared to what it is expected, or the ideal value in the ENV model. Otherwise, if the compressor elaborates a higher flow of compressed air, it means that the dryer cannot produce as much dry air as is required downstream. Consequently, the problem to be solved is to prevent flow losses inside the dryer.

Reformulating the problem according to the MTS model, the objective become: "How can the Technical system continue to perform the Function during use, always as designed?".

Then, we can search only those components of the air dryer that might break or degrade during use, as prescribed by step 2 of the proposed methodology. Consequently, we can determine which parts or components of the Technical system should not break so as not to affect the realization of Function, as prescribed by step 3 of the proposed methodology. After this reformulation, the problem becomes: "How to reduce the pressure drop inside the tank where the drying takes place".

A Possible solution to this problem, which was obtained by using TRIZ Inventive Principle N.15 "Dynamicity", regards the introduction of a mobile membrane. The objective of this device is to modify the internal volume of the tank, by moving exactly when required, or during the malfunction. After the malfunction is terminated, the mobile membrane returns to the initial position, by restoring the initial volume of the tank and the standard functioning of the system. TRIZ method is also strategic as a suggestion of resources to be used to make the identified solutions work. In this case, the most obvious resource to be used to move the membrane is the difference of pressure of the gas within the plant, which is caused by the variation of the fluid dynamic parameters after the pressure drop inside the tank. In turn the restoring of the parameter also provide the return of the membrane to its initial position.

3 Conclusions

This paper has helped to show how the problem of reducing variations in environmental impacts can be tackled in different ways, although the literature still lacks a single, shared, pragmatic, and rigorous approach to environmental aspects.

To fill this gap, the proposal concerns the integration of eco-assessment, design theories and robust design, to reformulate the initial problem in a more suitable way to be solved by a designer and more aware of the environmental aspects.

The results obtained, also through the provided case study, although the result of theoretical speculation, are useful in showing the variety of aspects to be considered and the heterogeneity of the topic, which can be addressed in many ways.

The approach followed, however, allows them to be compared and linked together. For this reason, it could constitute the basis of a structured case-based reasoning methodology, which is the main future development planned for this work.

References

1. Kania, A., Roszak, M., Spilka, M.: Evaluation of FMEA methods used in the environmental management. Arch. Mater. Sci. Eng. **65**(1), 37–44 (2014)
2. Zeng, S.X., Tam, C.M., Tam, V.W.: Integrating safety, environmental and quality risks for project management using a FMEA method. Eng. Econ. **66**(1) (2010)
3. Cherrafi, A., Elfezazi, S., Chiarini, A., Mokhlis, A., Benhida, K.: The integration of lean manufacturing, Six Sigma and sustainability: a literature review and future research directions for developing a specific model. J. Cleaner Prod. **139**, 828–846 (2016)
4. Panchal, D., Mangla, S.K., Tyagi, M., Ram, M.: Risk analysis for clean and sustainable production in a urea fertilizer industry. Int. J. Qual. Reliab. Manage. (2018)
5. Siler-Evans, K., Azevedo, I.L., Morgan, M.G., Apt, J.: Regional variations in the health, environmental, and climate benefits of wind and solar generation. Proc. Natl. Acad. Sci. **110**(29), 11768–11773 (2013)
6. Kim, S., Dale, B.E.: Regional variations in greenhouse gas emissions of biobased products in the United States—corn-based ethanol and soybean oil. Int. J. Life Cycle Assess. **14**(6), 540–546 (2009)
7. Olsson, P., Galaz, V., Boonstra, W.J.: Sustainability transformations: a resilience perspective. Ecol. Soc. **19**(4) (2014)
8. Redman, C.L.: Should sustainability and resilience be combined or remain distinct pursuits?. Ecol. Soc. **19**(2) (2014)
9. Gremyr, I., Siva, V., Raharjo, H., Goh, T.N.: Adapting the robust design methodology to support sustainable product development. J. Cleaner Prod. **79**, 231–238 (2014)

10. Bruno, F., Muzzupappa, M.: Product interface design: a participatory approach based on virtual reality. Int. J. Hum Comput Stud. **68**(5), 254–269 (2010)
11. McGrenere, J., Ho, W.: Affordances: clarifying and evolving a concept. Graph. Interface. **2000**, 179–186 (2000)
12. Kaptelinin, V.: Affordances and design. The interaction design foundation (2014)
13. Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I.: Life Cycle Assessment. Springer (2018). https://doi.org/10.1007/978-3-319-56475-3
14. Spreafico, C., Russo, D.: Assessing domestic environmental impacts through LCA using data from the scientific literature. J. Cleaner Prod. **266**, 121883 (2020)
15. Spreafico, C., Russo, D.: Exploiting the scientific literature for performing life cycle assessment about transportation. Sustainability **12**(18), 7548 (2020)
16. ISO 14040:2006 Environmental Management - LCA - Principles and Framework (2006)
17. Altshuller, G.S.: Creativity as an exact science: the theory of the solution of inventive problems. Gordon and Breach (1984)
18. Regazzoni, D., Russo, D.: TRIZ tools to enhance risk management. Procedia Eng. **9**, 40–51 (2011)
19. Russo, D., Spreafico, C.: TRIZ-based guidelines for eco-improvement. Sustainability **12**(8), 3412 (2020)
20. Russo, D., Spreafico, C., Spreafico, M.A.: Simplified TRIZ approach involving technology transfer for reducing product energy consumption. In: Scholz, S.G., Howlett, R.J., Setchi, R. (eds.) Sustainable Design and Manufacturing 2020, pp. 129–138. Springer, Singapore (2021). https://doi.org/10.1007/978-981-15-8131-1_12
21. Russo, D., Peri, P., Spreafico, C.: TRIZ applied to waste pyrolysis project in Morocco. In: Benmoussa, R., De Guio, R., Dubois, S., Koziołek, S. (eds.) International TRIZ Future Conference, pp. 295–304. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-32497-1_24
22. Spreafico, C.: Quantifying the advantages of TRIZ in sustainability through life cycle assessment. J. Cleaner Prod. **303**, 126955 (2021)

Data-Driven Predictive Maintenance in Evolving Environments: A Comparison Between Machine Learning and Deep Learning for Novelty Detection

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Abstract. Predictive Maintenance (PdM) is the newest strategy for maintenance management in industrial contexts. It aims to predict the occurrence of a failure to minimize unexpected downtimes of equipment and maximize the useful life of the monitored components. In a data-driven approach, PdM makes use of Machine Learning (ML) algorithms to extract relevant features from historical signals, identify and classify possible faults (diagnostics), and predict the components' remaining useful life (RUL) (prognostics). The major challenge lies in the high complexity of industrial plants, where both operational and environmental conditions change over time and a large number of unknown a priori modes may occur. A solution to this problem is offered by novelty detection, where a representation of the normal operating state of the machinery is learned and compared with online measurements in order to identify new operating conditions. In this paper, a comparison between ML and Deep Learning (DL) methods for novelty detection is conducted, to evaluate their effectiveness and efficiency in different scenarios. To this purpose, a case study considering vibration data collected from an experimental platform is carried out. Results show the superiority of DL on traditional ML methods in all the evaluated scenarios.

Keywords: Predictive maintenance · Novelty detection · Deep learning

1 Introduction

As one of the pillars of the Industrial 4.0 paradigm, predictive maintenance (PdM) is attracting researchers and practitioners of several industrial sectors. PdM allows performing maintenance interventions before a failure takes place and maximizing the useful lives of production [1]. Thanks to enabling technologies like IIoT and edge computing, it is possible to collect a large amount of data from online condition monitoring systems in order to assess the health condition of machinery at any point in time [2].

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The transformation of raw data in useful knowledge supporting the decision making process in the context of PdM is usually referred to as Prognostics and Health Management (PHM). This process mainly consists of feature extraction, fault detection and diagnosis, and prognostics [3]. A data-driven PHM approach makes use of condition monitoring techniques and machine learning (ML) algorithms to perform fault diagnostics and prognostics [4]. However, their industrial applicability is limited by the fact that the training data available to build diagnostic models typically do not include all the work conditions that components and systems may experience during their life [5, 6]. In addition, the data collected through an online condition monitoring system refer to equipment under varying operating and environmental conditions. In the literature, semi-supervised and self-adaptable approaches are proposed for fault diagnosis in evolving environments [5]. In these contexts, the occurring of a different operating condition is seen as a concept drift detection problem. When a concept drift is detected, existing diagnostic models are re-trained including new available data. Thus, the main goal is to detect abrupt concept drifts which correspond to the occurrence of a novel operating condition. The concept of drift detection can be considered as a novelty detection problem [7]. According to [8], novelties here are seen as agglomerations of abnormal observations, i.e., anomalies, representing a fundamental change in the underlying processes generating the observations. Hence, novelty detection can also be seen as a one-class classification problem [9]. Giving their promising results in several domains, e.g., feature learning, pattern recognition, time series forecasting, Deep Learning algorithms are receiving great attention in the context of novelty detection. However, a comparison in terms of classification performance between ML and DL algorithms is still missing in the field of novelty detection. In addition, existing studies only consider the case of one-class classification, including one only normal condition during the learning process. This aspect limits their application to industrial machinery, which operates under several normal conditions.

The main goal of the present study is to compare ML and DL performance in the recognition of novel operating conditions of a system. In particular, two different scenarios and two different levels of analysis will be considered, in order to determine the best models, in terms of prediction accuracy, in offline and online scenarios and when a single point or a batch is considered during models training and testing. In addition, the performance of each method is also compared in terms of required computational times for both training and prediction, and with a varying training size.

The remaining of the paper is organized as follows. In Sect. 2, common models used in the context of novelty detection are briefly reviewed. In particular, details on models adopted for the comparative analysis are provided. Section 3 shows the results obtained by the application of those models on raw vibration signals collected from a test rig.

2 Methods for Novelty Detection

In general, novelty detection methods learn, during the training, a representation of the normal operation of the machinery and are used at serving time to identify deviations from this representation. During the test phase, they are therefore required to assign novelty scores to each test data and then categorize them as belonging to a new operating condition depending on whether the score exceeds a certain threshold or not [10].

The most common ML methods adopted for novelty detection are summarized in this section. The Local Outlier Factor (LOF) algorithm is an unsupervised anomaly detection method that computes the local density deviation of a given data point with respect to its neighbors. It considers as outliers the samples that have a substantially lower density than their neighbors [11]. The Isolation Forest 'isolates' observations by randomly selecting a feature and then randomly selecting a split value between the maximum and minimum values of the selected feature. Since recursive partitioning can be represented by a tree structure, the number of splits required to isolate a sample is equivalent to the path length from the root node to the terminating node. This path length, averaged over a forest of such random trees, is a measure of normality and our decision function. Random partitioning produces noticeably shorter paths for anomalies. Hence, when a forest of random trees collectively produces shorter path lengths for particular samples, they are highly likely to be anomalies [12]. The One-Class Support Vector Machine is an unsupervised learning algorithm that is trained only on the 'normal' data, in our case the negative examples. It learns the boundaries of these points and is therefore able to classify any points that lie outside the boundary as outliers [13]. The Principal Component Analysis (PCA) is frequently used in exploratory data analysis because it reveals the inner structure of the data and explains the variance in the data. PCA looks for correlations among the variables and determines the combination of values that best captures differences in outcomes. For anomaly detection, each new input is analyzed, and the anomaly detection algorithm computes its projection on the eigenvectors, together with a normalized reconstruction error. The normalized error is used as the anomaly score. The higher the error, the more anomalous the instance is [14]. Online clustering can be considered a distance-based novelty detection approach, in which the "normal" class is characterized by a small number of prototype points in the data space [10]. During the prediction step, the distance between the "normal" points and new points is computed. A threshold is set to determine whether the current pattern belongs to the same cluster as the normal one, or creates a new cluster. Among DL approaches, the most widely adopted methods for novelty and anomaly detection problems are autoencoders. They are neural architectures that compress the input data into a compact vector representation (encoding phase) and try to reconstruct the original data starting from this intermediate representation (decoding phase) [9, 10, 15]. In the context of novelty detection, these architectures identify new operating conditions when the reconstruction error obtained exceeds a certain threshold, which confirms that the processed input cannot refer to any normal condition encountered in the training phase. This generic architecture can be implemented using different types of neural networks: simple Feed-Forward neural networks, Convolutional Neural Networks (CNNs) or Recurrent Neural Networks (RNNs). Feed-Forward AutoEncoder [9] relies on Multilayer Perceptrons, or MLPs for short, to encode and decode the input data and intermediate representations respectively. CNN AutoEncoder [15] applies convolutive filters to an input organized in a grid to derive an intermediate representation that encodes the spatial proximity information of the original data (encoding phase) and adopts an inverse strategy to re-expand this intermediate knowledge. RNN AutoEncoder [10] (LSTM in our case) is based on a recurrent connection of hidden representations generated from multiple MLPs, which is exploited to compress and reconstruct data while preserving their sequentiality and order of occurrence.

3 Experimental Evaluation

For the purpose of the present study, an experimental platform was built in the Department of Industrial Engineering of the University of Bologna. Several tests have been conducted to get vibration signals and apply the methods described in the previous section. The goal of this analysis is to provide a comparative evaluation of them in terms of effectiveness and efficiency in order to understand the main trade-offs deriving from their use. In particular, two scenarios are considered. In the first scenario, named offline, the models are first trained on a single operating condition; then, their ability to discriminate between the known condition and the other, i.e., novel conditions, was analyzed; this scenario corresponds to the common approach, which requires the re-train of models each time a new condition occurs; in the second scenario, named online, the models are evaluated in terms of their ability to incorporate new knowledge. This scenario evaluates an incremental learning approach, in which the ability to learn machinery conditions that were unknown at the time of the initial offline training is assessed. In addition, for each scenario, two levels of analysis are conducted. In the first case, each sample is considered separately; the prediction accuracy is computed by Eq. 1, where N is the number of samples, *1(x)* is converts the outcome of a boolean condition (true or false) into 1 or 0, y_i and $\tilde{y}_i$ represent the true and the predicted labels for the i-th sample, respectively

$$Accuracy\ (Acc) = \frac{1}{N}\sum_{i=1}^{N} 1(y_i = \tilde{y}_i) \tag{1}$$

A second level of analysis considers a batch of samples instead of single samples. In this case, the batch accuracy is given by Eq. 2, where $|B_k|$ indicates the cardinality of the k-th batch, with $k = 1, \ldots, M$ and M the number of batches, $y_{k,j}$ and $\tilde{y}_{k,j}$ represent respectively the true and the predicted labels for the j-th sample in the k-th batch.

$$Batch\,Accuracy\ (B.Acc) = \frac{1}{M}\sum_{k=1}^{M} 1\Big(\sum_{j=1}^{|B_k|} 1\big(y_{k,j} = \tilde{y}_{k,j}\big) = |B_k|\Big) \tag{2}$$

Hence, a prediction is considered correct when all the samples of a batch are correctly predicted. Finally, the performance of each model is also evaluated in terms of computational time of both training and testing.

The Dataset. The platform is shown in Fig. 1. It is composed of an asynchronous motor, a gearbox made of two pulleys that exchange the rotation through a belt, two shafts that share the motion thanks to a couple of gears, and an electromagnetic brake. The platform is provided with three triaxial accelerometers, which are placed on the bearing's support, next to the second pulley and the two gearboxes, respectively. They have a sampling frequency of 12.8 kHz per axis and an acceleration range of 500 Gpeak. A complete description of the platform can be found in [17]. For the purposes of experimentation, tests in four distinct operating conditions and a fault condition are conducted. The rotational speed is fixed at 660 rpm, while the distance between the pulley and the braking torque varies. The parameters, the duration, and the number of batches of each condition are shown in Table 1. Note that each batch has a length of 10 min. A representation of the raw signals in the 4 operating conditions is provided in Fig. 1. The considered signals represent a multivariate series where each feature is an acceleration. As can be seen, while the accelerations in the first operating condition are rather stable, significant oscillations occur in the other conditions, but only state 4 describes an anomalous operation of the machinery (i.e. states 1–3 represent normal operating conditions). Note that, since C4 is a fault condition, it will be used only as test data (i.e. no model will be trained on this anomalous state).

Table 1. Dataset description

Operating conditions	Distance between pulleys (mm)	Braking torque (Nm)	Duration (min)	Number of batches
C1	27.33	0.1	70	7
C2	27.33	0.5	150	15
C3	27.54	0.1	70	7
C4	27.54	0.1	30	3

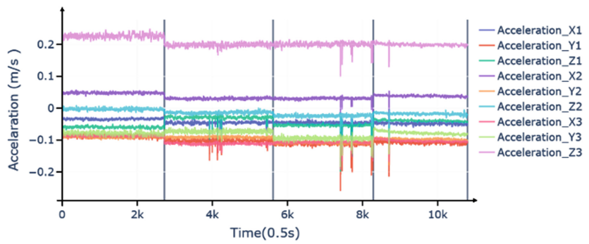

Fig. 1. Raw signals corresponding to each operating condition

Offline Evaluation Scenario. To carry out this evaluation we trained the models in turn on one batch at a time and we evaluated them on the remaining batches. This evaluation is repeated until each batch has been used for model training. The behavior we expect to obtain is that for all the test data associated with the same machine condition used for the training no novelty state is detected, while new machinery conditions are detected for the other samples. The results of this experiment are shown in Table 2, where for each model and training machinery condition, the accuracy, given by Eq. 1, and the batch accuracy, given by Eq. 2, computed over all the datasets are reported. The models that provide the worst performance are SVM, IF and LOF, while the remaining models are almost equivalent. With the exception of C3 where they produce poor results, these three models generate good performance on single samples (i.e. they obtain accuracy values in the range 0.66–0.97), however, in batch-level evaluation, they produce many false alarms (i.e. they obtain batch accuracy values in the range 0.3–0.6). Furthermore, it is possible to see how the most difficult operating condition to identify is C3, in which SVM, IF and MLP show the most significant reductions in performance, while C1 is recognized by the models with the highest effectiveness. This differentiation in performance does not apply to LSTM and CNN which are highly effective on all scenarios without distinction.

Table 2. Breakdown of model performance by operating condition

Algorithm	All		C1		C2		C3	
	Acc.	B. Acc.	Acc.	B. Acc.	Acc.	B. Acc.	Acc.	B. Acc.
Clustering	0.988	0.758	0.998	0.941	0.978	0.627	0.995	0.830
LOF	0.817	0.572	0.990	0.840	0.915	0.544	0.411	0.326
PCA	0.965	0.808	0.999	0.945	0.939	0.752	0.981	0.772
SVM	0.658	0.351	0.982	0.715	0.703	0.290	0.189	0.067
IF	0.880	0.619	0.994	0.867	0.967	0.598	0.561	0.379
MLP	0.957	0.911	1.000	1.000	0.945	0.906	0.933	0.821
LSTM	0.989	0.944	0.998	0.977	0.984	0.927	0.990	0.942
CNN	0.989	0.939	0.998	0.980	0.984	0.919	0.989	0.933

Online Evaluation Scenario. Drawing inspiration from [7], in this experiment we simulate the adoption of the models in a dynamic scenario where a continuous monitoring of the machinery is performed, and an incremental knowledge of the operating conditions of the machinery is learned by the diagnostic system. To create this experimental scenario we have considered the three settings shown in Table 3.

Table 3. Online scenario configurations

Conf	Training set	Test set	
		Known set	Novel set
S1	C1 (10 min)	C1 (70 min)	C2, C3, C4 (150 + 70 min + 10 min)
S2	C1, C2 (10 + 10 min)	C1, C2 (70 + 150 min)	C3, C4 (70 min + 10 min)
S3	C1, C2, C3	C1, C2, C3	C4

In the first configuration, each model is trained exclusively on a 10-min batch of C1 and an operating cycle is then applied to the other machinery settings. In the second configuration, it is assumed that the model has also learned of the existence of C1 and C2, and the same operating cycle is applied to other machinery settings. Finally, the last configuration evaluates the behavior of each model when trained jointly on all three states. Note how each model stores for each state a limited amount of data compared to the totality of measurements made (i.e. only 10 min of data for each state are considered). In this way 1) the model is trained quickly and it can continue to monitor the behavior of the machinery and 2) no dedicated storage is needed to store the entire measurement history. Results of this scenario are reported in Table 4, where for each model the batch accuracy is reported both for the entire test set, i.e., all observations included in both known and novel tests as defined in Table 3, and the known and novel sets as defined in Table 3, individually. Similar results were obtained considering the record-level accuracy, which were not reported due to space constraints. From Table 4, it is possible to observe that the configuration where the models perform best is the first one (S1), where the models are trained exclusively on C1. This confirms that C1 is significantly different from the other states, thus facilitating its distinction with respect to the other states. In this configuration, the worst-performing models are SVM, LOF, and IF, which correctly recognize C2, C3, and C4 as new operating conditions, however they tend to wrongly categorize batches belonging to C1. In the second configuration, on the other hand, there is a significant reduction in the effectiveness of the models, with the exception of LSTM and CNN. In more detail, the LOF, PCA, and Clustering models hardly recognize C1 and C2 as already known operating conditions (low accuracies on the known set). This is probably due to the integration of C2 with the training data, which has made the separation between the operating conditions less marked. Finally, by analyzing the third configuration, it is possible to note how all the models produce good performance in recognizing the known set, however they are no longer able to discriminate it with respect to the state C4, which actually presents, in the phase preceding the failure, very similar characteristics compared to other conditions. In particular, all models except LSTM and CNN have an accuracy equal to 0, i.e. they cannot correctly predict even a batch. A more detailed analysis of these results revealed that the record-level accuracy of these models varies in the range 0.1–0.33, while for LSTM and CNN in the range 0.81–0.83.

Table 4. Models batch accuracy in online scenario

Algorithm	C1			C2			C3		
	Test	Known	Novel	Test	Known	Novel	Test	Known	Novel
Clustering	0.941	0.732	1.000	0.567	0.503	0.700	0.410	0.455	0.000
LOF	0.840	0.304	0.990	0.456	0.395	0.586	0.690	0.767	0.000
PCA	0.945	0.750	1.000	0.235	0.000	0.729	0.000	0.000	0.000
SVM	0.715	0.321	0.825	0.618	0.565	0.729	0.790	0.878	0.000
IF	0.867	0.411	0.995	0.618	0.626	0.600	0.757	0.841	0.000
MLP	1.000	1.000	1.000	0.871	1.000	0.600	0.900	1.000	0.000
LSTM	0.997	0.893	1.000	0.935	0.952	0.900	0.743	0.772	0.476
CNN	0.980	0.911	1.000	0.922	0.912	0.943	0.790	0.847	0.286

To further inspect the superiority shown by the LSTM-based AutoEncoder over competitive methods, we propose in Fig. 2 a visual inspection of its internal representation for the examined operating conditions. In the figure this representation is compared with the raw distribution of operating states when projected into a two-dimensional space generated by the popular t-SNE technique [15]. As you can see, the embedded space created by the LSTM emphasizes the separation between the different operating conditions more than in the original feature space.

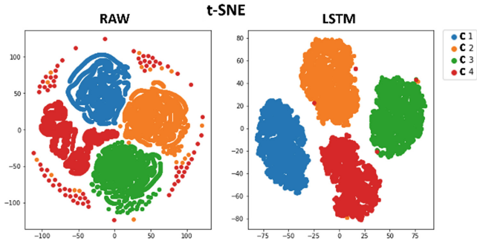

Fig. 2. LSTM-based AutoEncoder embedded space compared with the original feature space

Impact of Data Size on Performance. In this subsection, the impact of the size of the training data on model performance and computation time is assessed. For the evaluation of the performance, each model is trained on a variable number of batches associated with the same machinery state, i.e. 5, 10, 20 and 30 min of data. Each model is then required to recognize the test data as referring to a novel or already known condition of the machinery. Results of this experiment are shown in Fig. 3, where for each model the evolution of batch accuracy as the training size increases is reported for all the three states considered. Results show that the performance of deep learning models is high even with a small amount of training data (e.g., 5 min) and is not influenced by the availability of further training data. As for the other approaches, the variable availability of training data influences their performance (with the exception of the PCA which produces equivalent results for all the settings considered). In particular, Clustering and SVM are more effective as the size of the training set increases: SVM achieves accuracy improvements in the range between 9–20%, while Clustering between 6–20%. Similar trends are also confirmed for the LOF and IF models on C1 and C2. However, the latter two models perform worse as the size of the training set increases when trained on C3. A more detailed analysis of these results has revealed that in this setting they are unable to distinguish new states (i.e., LOF and IF generate a batch accuracy of 3 and 6%, respectively). The evaluation of computational time with varying training size is conducted to assess 1) the impact of a training process on the inactivity of each model, and 2) their velocity in detecting possible new operating conditions of the machinery (i.e., the prediction time). Note that models are run on a VM deployed on Google Cloud with 12 GB of RAM, GPU K80, and Intel(R) Xeon(R) CPU @ 2.30 GHz. For each model, both training and test times are considered. Each model is trained on 5, 10, 20 and 30 min of data and the relative times are recorded. In addition, the prediction time over 1 sample, 10-, 20- and 30-min batches was also recorded. The results of these two experiments are displayed in Fig. 4 on the left and right plots respectively. From the plot on the left in Fig. 4, it is possible to observe how the models require very different training times. Models like SVM and PCA only take a few milliseconds to complete the training. Times equal to almost two orders of magnitude are instead produced by IF and MLP models. Clustering and CNN, on the other hand, require times in the order of a second or a few tens of seconds. Finally, the LSTM model is the one that produces the highest training times: from 4 min in the configuration with fewer data to a maximum of 20 min. A confirmation of these trends is obtained by analyzing the prediction times shown in the right plot, although the latter are two orders of magnitude lower. From these results it is also possible to note that the Clustering approach produces significantly higher prediction times than the other techniques (with the exception of LSTM). This is due to the quadratic nature of the approach, although it was partially alleviated through a mixed training strategy where a first clustering solution was produced from 1000 samples and then the remaining data were included in an online fashion. Finally, it is possible to observe how the time required to evaluate whether a single sample belongs to an already known or novel state is a few milliseconds, making them all suitable for operating in an online scenario.

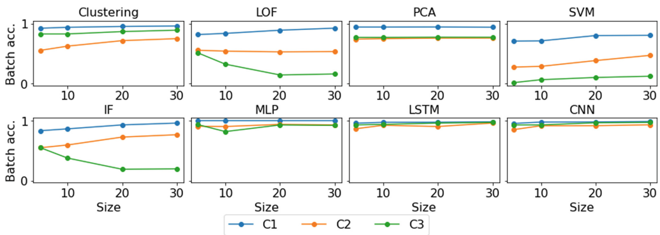

Fig. 3. Performance evaluation as the training size increase

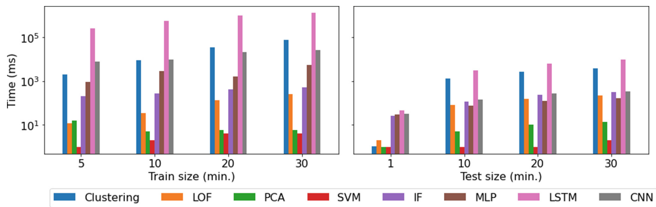

Fig. 4. Train (left) and test (right) performance by varying the data size

4 Conclusions

In this paper we have provided a comparative analysis of the performance of traditional techniques (e.g. Clustering, LOF, PCA, SVM, IF) and more advanced approaches based on deep learning models (Autoencoder, CNN) for novelty detection tasks in the context of fault diagnosis under varying operating conditions. The evaluation has been conducted in multiple test scenarios. The effectiveness was measured both in offline and online settings, in order to compare the ability of the models to exploit already known information and to incorporate new ones for the purpose of novelty detection. Furthermore, a variable dimension of the data was considered to analyze their impact on the time and effectiveness performance of these techniques. The main outcomes of the evaluation can be summarized as follows. First, traditional methods are less effective than DL-based models, however the latter requires more time for both training and inference. Second, methods based on autoencoders have shown greater robustness to noisy signals than competitive approaches. In summary, these results support the direction towards a beneficiary use of Deep Learning techniques in the context of novelty detection. Results in terms of testing times are promising for industrial streaming applications of fault diagnostics under dynamic environments. Further assessments in more complex scenarios will be conducted to verify the generality of this consideration.

References

1. Ayvaz, S., Alpay, K.: Predictive maintenance system for production lines in manufacturing: a machine learning approach Using IoT data in real-time. Expert Syst. Appl. **173**, 114598 (2020)
2. Cakir, M., Guvenc, M.A., Mistikoglu, S.: The experimental application of popular machine learning algorithms on predictive maintenance and the design of IIoT based condition monitoring system. Comput. Ind. Eng. **151**, 106948 (2021)
3. Jardine, A.K.S., Lin, D., Banjevic, D.: A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech. Syst. Signal Process. **7**(20), 1483–1510 (2006)
4. Çinar, Z.M., Nuhu, A.A., Zeeshan, Q., Korhan, O., Asmael, M., Safaei, B.: Machine learning in predictive maintenance towards sustainable smart manufacturing in Industry 4.0. Sustain **12**(19), 8211 (2020)
5. Hu, Y., Baraldi, P., Di Maio, F., Zio, E.: A systematic semi-supervised self-adaptable fault diagnostics approach in an evolving environment. Mech. Syst. Signal Process. **88**, 413–427 (2017)
6. Calabrese, F., Regattieri, A., Botti, L., Mora, C., Galizia, F.: Unsupervised fault detection and prediction of remaining useful life for online prognostic health management of mechanical systems. Appl. Sci. **10**(12), 4120 (2020)
7. Cariño, J.A., et al.: Fault detection and identification methodology under an incremental learning framework applied to industrial machinery. IEEE Access **6**, 49755–49766 (2018)
8. Gruhl, C., Sick, B., Tomforde, S.: Novelty detection in continuously changing environments. Futur. Gener. Comput. Syst. **114**, 138–154 (2021)
9. Pimentel, M.A.F., Clifton, D.A., Lei, A., Tarassenko, L.: A review of novelty detection. Signal Process. **99**, 215–249 (2014)
10. Pang, G., Shen, C., Cao, L., Hengel, A.: Deep learning for anomaly detection: a review. ACM Comput. Surv. **54**(2), 1–38 (2021)
11. Breunig, M., et al.: LOF: identifying density-based local outliers. In: SIGMOD/PODS00: ACM International Conference on Management of Data and Symposium on Principles of Database Systems. Dallas Texas USA, May 2000
12. Wei, X., Ling, H., Fox, A., Patterson, D., Jordan, M.: Large-scale system problems detection by mining console logs. In: 22nd ACM Symposium on Operating Systems Principles, Montana (2009)

13. Schölkopf, B., et al.: Estimating the support of a high-dimensional distribution. Neural Comput. **13**(7), 1443–1471 (2021)
14. Liu, F.T., Ting, K.M., Zhou, Z.-H.: Isolation-based anomaly detection. ACM Trans. Knowl. Disc. Data (TKDD) **6**(1), 1–39 (2012)
15. Li, X., Li, X., Ma, H.: Deep representation clustering-based fault diagnosis method with unsupervised data applied to rotating machinery. Mech. Syst. Signal Process **143**, 106825 (2020)
16. Van der Maaten, L., Hinton, G.: Visualizing data using t-SNE. J. Mach. Learn. Res. **9**(11), 53 (2008)
17. Calabrese, F., Regattieri, A., Bortolini, M., Gamberi, M., Pilati, F.: Predictive maintenance: a novel framework for a data-driven, semi-supervised, and partially online prognostic health management application in industries. Appl. Sci. **11**(8), 3380 (2021)

Visualising Sustainability-Related Information: A Review of Visualisation for Sustainability in Manufacturing Industry

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Abstract. Industrial sustainability is attracting more and more attention in recent years. But sustainability data can be complex, hard to collect, and difficult to explain and use. We draw on visualisation research to improve the utility of sustainability-related information, which we categorise as normally being "invisible". Better visualisation will facilitate practitioners to understand sustainability performance and eventually encourage better decisions to improve the sustainability performance of manufacturing industry. This research conducts a literature review through keywords searching. After filtering 319 results, we identified 28 papers as relevant ones and thematic analysis of the identified papers was conducted to understand their contents. The results of the literature review show that Life Cycle Assessment (LCA), Sustainable Value Stream Mapping (Sus-VSM), Sankey diagram, etc., appear from the identified papers as visualisation tools or methods. We revealed two levels of visualisation on sustainability-related information, they are, assessment of sustainability and presentation of data, while the second level attracts less attention. Although some papers suggested that visualisation facilitates decision-making for improving sustainability performance, few studies paid attention to the effects of the visualisation. In the last, we also suggest dynamic visualisation as one of the potential developing directions for the visualisation of sustainability-related information, while the utility of creating such a dynamic system needs to be carefully analysed in advance.

Keywords: Visualisation · Sustainable production · IoT · Decision-making · Behaviour change · Literature review

1 Introduction

Sustainability issues are becoming more and more crucial in recent years. The industry is the largest sector of energy consumption accounting for nearly 25% of global energy usage in 2019 and is the largest sector of CO_2 emission accounting for over 30% of the global GHG emission in 2010 [1, 2]. Based on these facts, industries have adopted

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many approaches and tools to assess and analyse their sustainable performance. The very first step of doing so is to measure and collect sustainability-related information, which eventually influences or represents environmental performance. In this research, attentions are specifically paid to manufacturing industry and sustainability information includes consumption of materials, resources, water, energy (electricity, gas, etc.), CO_2 as well as wastes. Energy and CO_2 are physically "invisible"; therefore, proper tools and multiple sensors are necessary for visualising them. As for materials, water, resources and wastes, they are physically visible, but accurate data on inputs, outputs and flows are often not available. This is also the case for energy and CO_2. Even if all relevant data have been measured and collected, the data are often complex, in different systems, and different units. Hence there is still a challenge for practitioners to understand their characteristics and properly use them to improve sustainability performance.

As industry 4.0 is coming, more and more sensors are applied to production systems, which enables to collect and visualise sustainability-related data. Unfortunately, it still brings the question of how to use the enormous amount of data properly so that the effectiveness of accessing these data can be maximised. In industry, visualisation is always used to facilitate people to understand the situation of production and help them to make better decisions. For example, in lean manufacturing, value stream mapping is a typical tool to visualise the value chain of a production system, which is very helpful for practitioners to identify value-adding and non-value-adding activities [3]. However, proper visualisation of data needs to be analysed in order to promote actions and behaviours changes of practitioners so that they can improve the sustainability performance.

This paper aims to summarise current research about the visualisation of sustainability-related information by a literature review. It will try to answer the following research questions: RQ1: What is the visualisation used in manufacturing industry? RQ2: How are visualisations used in practice and how does visualisation facilitate practitioners for sustainability performance improvements? As it is a novel research area, thematic analysis was conducted for the identified papers after keywords searching and content selection. Based on the results of the literature review, the current focuses of visualisation of sustainability-related information from the academia will be discussed, associated with potential developing directions of sustainable visualisation tools. It has been found that the current visualisations are always used to illustrate the results of some sustainability assessment methods such as life cycle assessment (LCA); or used to display the invisible information such as energy, and one typical example can be Sustainable Value Stream Mapping (Sus-VSM) which is modified from Value Stream Mapping (VSM) and combined with sustainable features. In addition, it is argued that too much attention has been put on the visualisation itself while few papers talk about the effects of the visualisation. In other words, how on earth does the visualisation influence practitioners' decision-making and behaviour changes? At the end, a conclusion summarises the paper.

2 Research Methodology

The literature was searched initially in the database Scopus. The Scopus was selected as it is one of the biggest academic databases, therefore, the most related paper can be found. The literature review was conducted through keywords searching firstly. The target reviewing papers are under the topic of visualizing sustainability-related information of production for sustainability. In order to search the relevant papers, four groups of keywords were used, which are (visuali*) AND (waste OR energy OR electricity OR material OR resource OR CO_2 OR water) AND (sustainab*) AND (production OR industry OR factory OR manufactur*). "Visuali*" represents for "visualise" ("visualize"), "visualising" ("visualizing") and "visualisation" (visualisation), "sustainab*" represents "sustainable" and "sustainability", while "manufactur*" represents "manufacture", "manufacturing" and "manufacturer". 634 results were found on the database Scopus, and 319 papers were English academic journal paper within these 634 papers. Then, all the abstracts of the 319 searched papers were reviewed by the author to eliminate papers with the selected keywords but out of the scope of the research. (The search was conducted on 24 January 2021.)

The selection process is shown in Fig. 1. The first step of the selection is to identify whether the research is within the scope of manufacturing industry and production or not. The second step is to identify if the visualising contents are sustainability-related information. The third step is to figure out if the purpose of the visualisation is for sustainability. Following such a process, 28 papers were eventually identified as the most relevant.

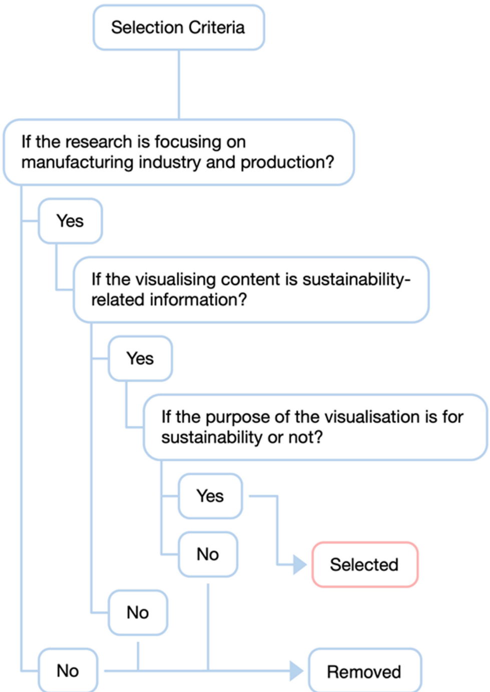

Fig. 1. Selection process of the searched papers

3 Results and Findings

3.1 Chronological Distribution

The chronological distribution of the identified 28 papers is shown in Fig. 2. The first identified paper following the mentioned selection process was published in 2012. This paper was published in Marine Policy and written by Hornborg, S. and his co-authors [4]. In the paper, the authors mentioned that LCA can visualise the environmental impacts of seafood production and be helpful in decision making. From Fig. 2, it can be found the number of publications by year has an upward trend (shown using the orange dashed line). In the year of 2020, there were six papers published under the topic, and it was the most productive year. Such a result indicates that the visualisation of sustainability-related information has continuously attracted attention.

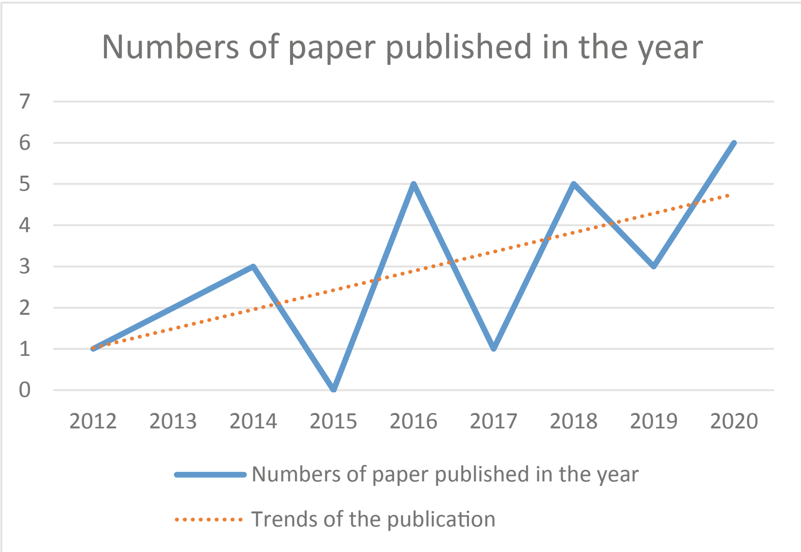

Fig. 2. Chronological distribution of the identified papers (not including the year 2021)

3.2 Analysis of Journals and Authors

The identified papers have been published in a variety of journals, which implies that visualisation has been used for different research areas and the research on visualisation of sustainability-related information has not formed a specific research sub-field. There are six papers published in the Journal of Cleaner Production, three papers published in Sustainability (Switzerland), as well as two papers published in the Environmental Progress and Sustainable Energy, International Journal of Life Cycle Assessment and Renewable and Sustainable Energy Reviews, respectively (shown in Fig. 3). The other 13 papers were published in 13 different journals.

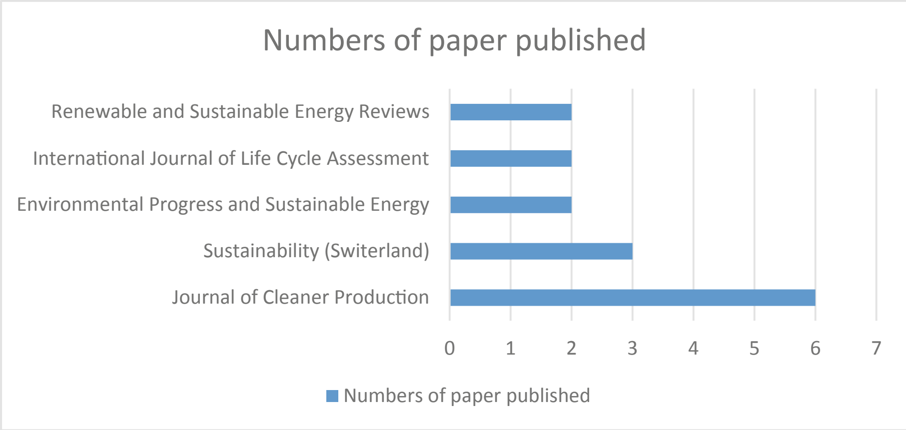

Fig. 3. Numbers of papers published in the top5 journals

As for authors, Ghannadzadeh and Sadeqzadeh published two papers together and they present their research results with visualised exergetic flowsheets [5, 6]. All other authors only contributed to one paper, which indicates again that few researchers started to pay substantive attention to this field. A special example is that Rönnlund and his collaborators published two papers under the same topic which were separated into Part 1 and Part 2. These two papers are considered as one paper here in the analysis of authors [7, 8].

3.3 Findings

Due to the novelty of the research questions, thematic analysis was conducted to understand the identified 28 papers. It is a qualitative research method for identifying, analysing and reporting the themes of the collected data which is very suitable for exploring the immature research areas [9, 10]. The identified 28 papers are identified into two themes: 1) illustrating the results of sustainability assessment tools, and 2) presenting the sustainability-related data throughout production processes (shown in Fig. 4).

For the first theme, various sustainability assessment tools are introduced to reveal sustainability issues that lack necessary attentions. 11 out of 28 papers used the visualisations to present their results of LCA, which is the biggest field. LCA is a tool to analyse environmental factors and the potential impact of a product or a service throughout its whole life cycle, from the cradle to the grave. With the LCA thinking, tools for different purposes can be further developed. For example, Sharma and his colleagues created a tool to visualise the hotpots of friction stir processing during different stages of a product life cycle to improve sustainability [11]. Moreover, exergy analysis with exergetic flowsheets was used by two papers to present their research outcomes [5, 6]. In addition to LCA and exergy analysis, there are some other sustainability assessment tools. For instances, Cai and Lai assessed the sustainability in mechanical manufacturing system [12].

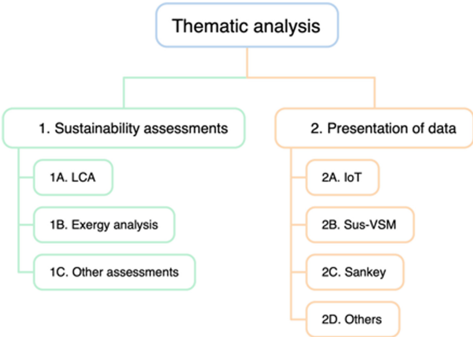

Fig. 4. Thematic analysis of the identified 28 papers

As for the second theme, due to the invisible nature of sustainability-related information, such as energy, electricity and CO_2 emissions, tools have been developed to measure, collect and visualise such information. Especially, the rapid development of Internet of Things (IoT), coming with the big background of Industry 4.0, has remarkably empowered the ability to do so in real-time. For example, Lavalle and his colleagues published a paper in 2019, discussing improving the sustainability of electricity production by facilitating practitioners to understand the potential failures with the help of an IoT based real-time system [13]. In addition, Brown, Amundson and Badurdeen developed Sustainable Value Stream Mapping based on the lean tool – Value Stream Mapping [14]. VSM is a typical tool used for identifying and visualising wastes of value, and Sus-VSM extends its efficacy and adds sustainability metrics into the tool. Sus-VSM provides a unique direction of developing visualisations of sustainability-related information. Another interesting finding is that some researchers used Sankey diagram as a decision support tool [15]. Sankey diagram can illustrate the flows of material, energy, elements, etc., which is commonly be used to present the results of material flow analysis (MFA).

At last, the findings of the literature review answer the first research question: what is the visualisation used currently in manufacturing industry? While as for the second research question, few studies on how visualisation affects the practitioners and facilitate improving sustainability were found which implies a research gap and a potential direction for future research.

4 Discussion

This literature review was conducted through keywords searching, therefore all papers under the selected topic that mentioned visualisation have been reviewed. However, due to the universality of visualisation, some papers might not be covered through the searching. Also, some papers might use visualisation but the word "visuali*" is not used in the titles, keywords and abstracts, therefore, these papers are also missing. As a result, the samples of this literature review (N = 28) are relatively small due to the particularity of the focused research topic. To further understand the visualisation of sustainability-related information, it might be helpful to conduct snowballing searching starting with the identified 28 papers. Also, the results have revealed some relevant keywords, such as LCA, Sus-VSM, Sankey, etc. Studying these topics could provide a further understanding of the visualisation of sustainability-related information. Nevertheless, with the identified 28 papers, there are some interesting findings for developing the visualisation tool of sustainability-related information that worth to be discussed. Figure 5 illustrates the proposed logic of how the visualisation of sustainability-related information improves sustainability performance.

From the results of the literature review, the identified two themes are indicating two levels of visualisation of sustainability-related information as shown in Fig. 5: 1) the assessment of sustainability, and 2) the presentation of the data. The first level of visualisation focuses on revealing the new or unaware environmental metrics of production through professional sustainability assessment tools from different aspects, such as LCA and exergy analysis. For example, LCA enables people to see the environmental impacts of one product or one service throughout its entire life cycle rather than just focusing on its manufacturing process in seafood production [4]. The environmental impacts of other phases of the product or the service can be invisible before applying LCA. While the second level of visualisation focuses on the presentation of the data, which can be the results of the assessment tools or sustainability-related data collected from the production process. Normally, it can be diagrams, figures, graphs or charts. Sankey diagram is one of the typical examples, which is used to present the results of LCA or Material Flow Analysis (MFA) [11, 15].

Although the identified papers are all relevant to visualisation, few papers have written about the design theory of the visualisation. Especially for the second level of visualisation, few papers mentioned how the presentation of the data influences the delivery of the content. Lavalle and her colleagues specifically proposed a guideline of defining the goals of visualisation when developing IoT based on real-time visualisation while such efforts have not been found in other papers [13]. In addition, a few papers mentioned that visualisation can be used as a support for decision-making [4, 11, 15–17]. However, few papers analyse how visualisation affects decisions (red arrows in Fig. 5). We believe that decision making is not a simple process, the design of the visualisation should consider its effects, e.g., which part of the production process needs to be improved, what countermeasures should be taken for effective improvements, etc. The identified papers pay much more attention to the visualisation itself, pursuing higher precision and finding new angles of seeing challenges rather than achieving practical impacts. Katzeff and his colleagues conducted a study on exploring sustainable practices in workplace setting through the visualisation of energy consumption [18]. They tried to study how people receive and interpret the visualisation, but the research was conducted in the workplace and it just focused on visualising the overall use of electricity rather than combined with the production process. A research gap between the assessment, collection and presentation of the sustainability-related data and decision-making, behaviour and action changes of practitioners emerges from the result of the literature review.

Last but not least, it has been found that the majority of the visualisation is presented in a static form. With the help of IoT sensors, factories can collect real-time data, which enables dynamic visualisation of sustainability-related information. A new approach is desirable to support decision-making taking into account dynamic changes, such as temporal changes, material and energy balance, and improvements due to various countermeasures. To this end, system dynamics could be used to enable dynamic simulations. However, it needs further research on whether it is worth creating such a dynamic system by comparing the efforts with the benefits on sustainability performance. The level of the dynamic should be carefully considered before setting up the system.

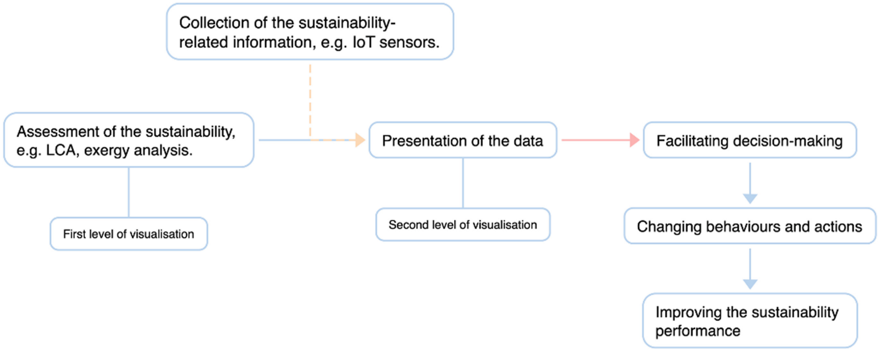

Fig. 5. How visualisation of sustainability-related information improves sustainability performance.

5 Conclusion

The visualisation of sustainability-related information can be a key factor for decision-making on improving sustainability performance. This paper conducted a literature review through keywords searching. Based on the identified 28 papers after filtering from 319 searched results, thematic analysis was conducted, and two levels of the visualisation have been revealed – the assessment of the sustainability and the presentation of data. It has been found that the current research pays more attention to the first level of visualisation, which aims at higher precision and better analysis. However, the delivery of information and the effects of the visualisation has hardly been studied. Therefore, a research gap between the visualisation of sustainability-related information and decision-making and behaviour and action changes has been identified. In addition, the IoT sensors enable collecting data in real-time, which allows developing dynamic visualisation. But the advantage of the dynamic visualisation compared to a static one needs to be further studied. To sum up, the visualisation of sustainability-related information can be essential for increasing practitioners' sustainable awareness and promoting sustainable decisions and actions, but the road between these two concepts needs to be further explored.

References

1. IPCC: AR5 Climate Change 2014: Mitigation of Climate Change, vol. 10, p. 16. Cambridge University Press, New York (2014)
2. IEA: IEA – International Energy Agency, IEA (2019). https://www.iea.org. Accessed 30 Aug 2020
3. Hines, P., Rich, N.: The seven value stream mapping tools. Int. J. Op. Prod. Manag. **17**(1), 46–64 (1997). https://doi.org/10.1108/01443579710157989
4. Hornborg, S., Nilsson, P., Valentinsson, D., Ziegler, F.: Integrated environmental assessment of fisheries management: Swedish Nephrops trawl fisheries evaluated using a life cycle approach. Mar. Policy **36**(6), 1193–1201 (2012). https://doi.org/10.1016/j.marpol.2012.02.017
5. Ghannadzadeh, A., Sadeqzadeh, M.: Evaluation of an alternative chlorine production process for energy saving toward sustainability. Environ. Prog. Sustainable Energy **35**(5), 1512–1520 (2016). https://doi.org/10.1002/ep.12374
6. Ghannadzadeh, A., Sadeqzadeh, M.: Cleaner production of purified terephthalic and isophthalic acids through exergy analysis. Int. J. Exergy **31**(4), 303–329 (2020). https://doi.org/10.1504/IJEX.2020.107189
7. Rönnlund, I., et al.: Eco-efficiency indicator framework implemented in the metallurgical industry: part 1—a comprehensive view and benchmark. Int. J. Life Cycle Assess. **21**(10), 1473–1500 (2016). https://doi.org/10.1007/s11367-016-1122-9
8. Rönnlund, I., et al.: Eco-efficiency indicator framework implemented in the metallurgical industry: part 2—a case study from the copper industry. Int. J. Life Cycle Assess. **21**(12), 1719–1748 (2016). https://doi.org/10.1007/s11367-016-1123-8
9. Braun, V., Clarke, V.: Using thematic analysis in psychology. Qual. Res. Psychol. **3**(2), 77–101 (2006). https://doi.org/10.1191/1478088706qp063oa
10. Vaismoradi, M., Turunen, H., Bondas, T.: Content analysis and thematic analysis: implications for conducting a qualitative descriptive study: qualitative descriptive study. Nurs. Health Sci. **15**(3), 398–405 (2013). https://doi.org/10.1111/nhs.12048
11. Sharma, R.K., et al.: Sustainability in manufacturing processes: finding the environmental impacts of friction stir processing of pure magnesium. CIRP J. Manuf. Sci. Technol. **30**, 25–35 (2020). https://doi.org/10.1016/j.cirpj.2020.03.007
12. Cai, W., Lai, K.-H.: Sustainability assessment of mechanical manufacturing systems in the industrial sector. Renewable and Sustainable Energy Rev. **135**, 110169 (2021). https://doi.org/10.1016/j.rser.2020.110169
13. Lavalle, A., Teruel, M.A., Maté, A., Trujillo, J.: Fostering sustainability through visualization techniques for real-time IoT data: a case study based on gas turbines for electricity production. Sensors (Switzerland) **20**(16), 1–19 (2020). https://doi.org/10.3390/s20164556
14. Brown, A., Amundson, J., Badurdeen, F.: Sustainable value stream mapping (Sus-VSM) in different manufacturing system configurations: application case studies. J. Clean. Prod. **85**, 164–179 (2014). https://doi.org/10.1016/j.jclepro.2014.05.101
15. Chen, P.-C., Liu, K.-H., Ma, H.-W.: Resource and waste-stream modeling and visualization as decision support tools for sustainable materials management. J. Clean. Prod. **150**, 16–25 (2017). https://doi.org/10.1016/j.jclepro.2017.02.173
16. Barletta, I., Larborn, J., Mani, M., Johannson, B.: Towards an assessment methodology to support decision making for sustainable electronic waste management systems: automatic sorting technology. Sustainability (Switzerland) **8**(1), 1–20 (2016). https://doi.org/10.3390/su8010084

17. Besseau, R., Sacchi, R., Blanc, I., Pérez-López, P.: Past, present and future environmental footprint of the Danish wind turbine fleet with LCA_WIND_DK, an online interactive platform. Renew. Sustain. Energy Rev. **108**, 274–288 (2019). https://doi.org/10.1016/j.rser.2019.03.030
18. Katzeff, C., Broms, L., Jönsson, L., Westholm, U., Räsänen, M.: Exploring sustainable practices in workplace settings through visualizing electricity consumption. ACM Trans. Comput. Hum. Interaction **20**(5), 1–22 (2013). https://doi.org/10.1145/2501526

Reconfigurable Manufacturing System Design Using a Genetic Algorithm

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Abstract. In the modern context governed by Industry 4.0, Reconfigurable Manufacturing Systems (RMSs) rose as an effective production strategy able to cope with the increased product variety, the dynamic market demand and the need for flexible production batches. The manufacturing environment is usually made of a set of intelligent machines, i.e. Reconfigurable Machine Tools (RMTs), consisting of basic and auxiliary modules, which allow performing different operations. In this context, this paper proposes an optimization model for the dynamic design of RMSs with alternative part routing and multiple time periods, aiming at determining the part routing mix and the auxiliary module allocation best balancing the part flows among RMTs and the effort to install the modules on the machines. The model is solved through the application of a genetic algorithm applying different crossover operators and different threshold values for the occurrence of crossover and mutation processes. Results from the considered instance highlight that the two point crossover operator allows achieving the lowest fitness value, i.e. the lowest value of the defined objective function, getting a manufacturing system configuration characterized by low inter-cell part flow and machine reconfiguration time.

Keywords: Reconfigurable manufacturing systems · Reconfigurability · RMS · Genetic algorithm · Optimization model

1 Introduction and Literature Review

In modern industry, manufacturers are facing a high level of market globalisation, increased product innovation and variety, dynamic customer demand and technological advancements [1, 2]. These trends encourage industrial companies to adopt the mass customisation paradigm to meet every customers' request and satisfy their individual needs. In this dynamic and changeable scenario, reconfigurability is one of the major enablers of changeability and, from the Industry 4.0 perspective, it is an essential element to cope with the ever-increasing complexity of the modern industrial and market scenario [3–5]. Reconfigurable Manufacturing Systems (RMSs) rose in 1999 as a new production system paradigm including changeability attributes at both physical and logical levels [6, 7] joining their core features of modularity, integrability, diagnosibility, convertibility,

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customization and scalability [4]. A typical RMS structure includes a set of intelligent machines called reconfigurable machine tools (RMTs) with an adjustable and modular structure through a set of basic and auxiliary custom modules, which allow to increase the set of feasible operations to perform [2, 8, 9]. In particular, each RMT incorporates a number of basic modules that are structural elements permanently attached to the machine, and a number of auxiliary modules, which are kinematical or motion-giving. Therefore, a specific combination of such modules provides a particular set of operational capabilities to the RMT. In current literature, a wide set of studies concerning optimization models for RMS design and management has been developed [10–12]. Youssef and ElMaraghy [13, 14] defined a novel algorithm supporting the RMS configuration selection with the goal to find the most suitable configurations for the different demand scenarios over the considered time horizon and to select those that allow minimizing the reconfiguration effort. In the same field, Moghaddam et al. [15] faced the RMS configuration design in presence of dynamic market demand. In such a context, the production system configuration needs to vary accordingly to the demand data at the minimum cost. To face this issue, the Authors developed a mixed integer linear programming formulation to manage the first manufacturing system configuration design as well as the further required configurations according to the dynamic demand rate. Goyal et al. [16] defined a multi-objective model to estimate the reconfigurability potential and task capability of RMTs according to the auxiliary module interactions. Moreover, the proposed mathematical algorithm supported the optimal part-machine assignment in case of a single part flow line allowing the parallel working of similar RMTs. Another wide group of researchers proposed to arrange RMSs in cellular production patterns, leading to the rise of Cellular Reconfigurable Manufacturing Systems (CRMSs) [9, 17, 18]. In conventional cellular manufacturing systems (CMSs), the formation of the manufacturing cells is an activity traditionally performed during the initial setup of the CMS and the layout does not change during the production life cycle. However, the recent trends imposed by Industry 4.0, e.g. mass production, dynamic market demand, etc., make CMSs obsolete because of the manufacturing cells may need to vary their structure throughout the production life cycle. To face this issue, recent studies suggest introducing the modularity attribute in the design of the manufacturing machines to include in the cells, enabling reconfigurability [8, 9]. In this field, Pattanaik et al. [8] proposed a clustering-based approach to design reconfigurable machine cells through adjustable machines. Eguia et al. [19, 20] defined a mathematical optimization model for the design of CRMSs aiming at minimizing the total inter-cell part movements and the overall production costs. According to this background, this paper proposes an optimization model for the dynamic design of CRMSs, best balancing the trade-off between the effort to reconfiguring the RMT hosting the part, in terms of auxiliary module installation and disassembly, versus the inter-cell part travel flows. The model is, then, applied to a numeric operative case study and solved by applying a genetic algorithm (GA). According to this background and the outlined goals, the remainder of this paper is organized as follows. Section 2 introduces the optimization model for CRMSs design while the description of the solving procedure is in Sect. 3. The application of the model to the operative reference case study and the results discussion are in Sect. 4. Finally, Sect. 5 concludes the paper with final remarks and future opportunities for research.

2 Optimization Model for the Design and Management of CRMSs

The aim of this section is to introduce and describe the optimization model for the dynamic design of CRMSs. The production context is made of a set of Reconfigurable Machine Cells (RMC) including a number of RMTs. Each RMT is characterized by a library of basic and auxiliary modules. As described in Sect. 1, the basic modules are structural elements permanently attached to the machines, while auxiliary modules are dynamic entities, which can be assembled and disassembled to/from the RMT when needed to provide different operational capabilities. Next Fig. 1 shows a conceptual framework of a typical CRMS structure, derived from [21].

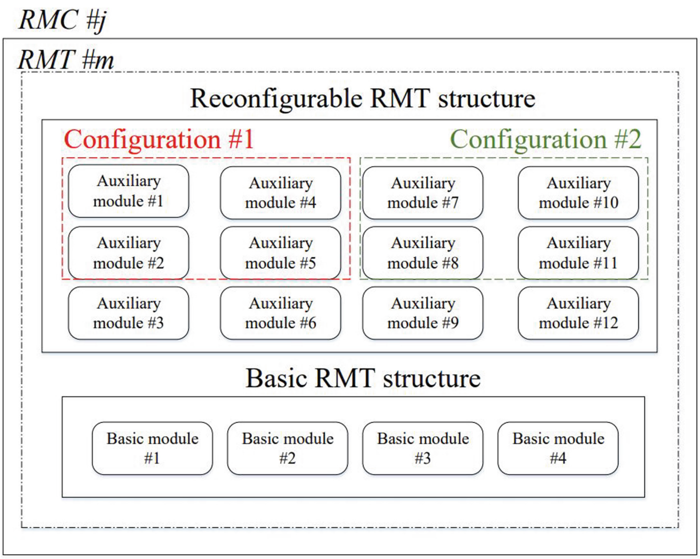

Fig. 1. Schematic of a cellular RMS structure, derived from [21].

2.1 Problem Description, Assumptions and Notations

The proposed CRMS model relies on an initial RMT-RMC assignment and explores how to best-balance the reconfigurability effort, i.e. assembly and disassembly of the auxiliary modules on/from the RMTs, and the part flow among the RMCs, by using the available information about the operation sequence and the compatibility among the auxiliary modules, operations and RMTs. To this aim, the model minimizes the sum of the inter-cell, i.e. inter-RMC, parts travel time and the reconfiguration time to assemble and disassemble the auxiliary modules defining the part batch flows and the most suitable allocation of the modules to the RMTs. For the sake of brevity, in the following, analytic details about model indices, parameters, variables and the objective function formulation will be provided; while the complete formulation of the logical constraints is omitted.

The following notations are used.

- Indices

i	parts $i = 1, \ldots, M$
j	RMCs $j = 1, \ldots, N$
k	modules type k $= 1, \ldots, K$
m	RMTs $m = 1, \ldots, Z$
o	operations in part work cycle $o = 1, \ldots, O_i$
t	time periods $t = 1, \ldots, T$

- Parameters

G_{omk}	1 if operation o can be performed on RMT m using an auxiliary module of type k; 0 otherwise $[binary]$
MAC_{mj}	1 if RMT m is assigned to RMC j; 0 otherwise $[binary]$
R	maximum number of modules per RMT and period [#]
r_{it}	definition of the operation in which the batch of part i is in period t
t_{ijj_1}	travel time for batch of part i from cell j to cell j_1 $[min/batch]$
λ_{mk}	assembly time of module type k on RMT $m[min/module]$
μ_{mk}	disassembly time of module type k from RMT m[min $/module$]
τ_{om}	time to perform operation o on RMT $m[min/op]$
ξ	available time per RMT $[min/machine]$
δ_i	planned production volume during a predefined period of time for part i $[parts]$

- Decisional Variables

F_{ijj_1t}	1 if batch of part i moves from RMC j to RMC j_1 in period t; 0 otherwise $[binary]$
W_{mit}	1 if batch of part i is processed by RMT m in period t; 0 otherwise $[binary]$
σ_{mkt}	1 if module type k is on RMT m in period t, 0 otherwise $[binary]$
X_{mkt}	1 if module type k is assembled on RMT m in period t, 0 otherwise $[binary]$
Y_{mkt}	1 if module type k is disassembled from RMT m in period t, 0 otherwise $[binary]$

- Objective function

$min\ \psi$ Part travel time and module assembly/disassembly time [min], as in (1)

$$\psi = \sum_{t=1}^{T}\sum_{m=1}^{Z}\sum_{k=1}^{K} X_{mkt}\cdot\lambda_{mk} + \sum_{t=1}^{T}\sum_{m=1}^{Z}\sum_{k=1}^{K} Y_{mht}\cdot\mu_{mk} + \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{j_1=1}^{N}\sum_{t=1}^{T-1} F_{ijj_1t}\cdot t_{ijj_1} \tag{1}$$

The first and the second terms are for the module assembly and disassembly time on/from RMTs, respectively, while the third term is for the part travel time. Next Sect. 3 introduces the procedure used to solve the model, based on GA.

3 Solving Procedure

The goal of the model is to determine the part batch flow among RMTs and RMCs as well as the best allocation of the auxiliary modules to the RMTs for part processing, considering the part work cycle and the compatibility information among auxiliary modules, operations and RMTs. Due to the model complexity, a heuristic method, i.e. GA, is chosen as solving method. GA relies on the concept of evolutionary computation reproducing the natural selection and biological reproduction of animal species. In fact, it originates from Darwin's "survival of the fittest" concept, meaning that a good parent produces better offspring, and it has been successfully applied over the time for flexible job-shop and flow-shop scheduling [22]. Prior to its application, GA requires to design the genetic representation, e.g. chromosome, of the candidate solutions. A chromosome represents each solution in the initial solution set of the population and it evolves through a crossover and a mutation operator to produce offspring, with the aim to improve the current set of solutions. The chromosomes are then evaluated through a fitness function, and the less fit chromosomes are replaced with better children. Such process of crossover, evaluation and selection is repeated for a number of iterations, usually up to the point in which the system ceases to improve. To summarize, Table 1 lists the main steps to follow for GA implementation to determine the optimum or near to optimum manufacturing configurations.

Table 1. Steps for GA implementation.

Genetic algorithm (GA) implementation steps
Step A: Parent selection
Step B: Crossover
Step C: Mutation
Step D: Fitness evaluation
Step E: Termination criterion

In this study, the step A, i.e. parent selection, is implemented according to the *roulette* method. Therefore, the probability of selecting a string is closely related to its fitness value. As reference example, in case of objective function to minimize, the lower the fitness of a string, the higher the probability that it will be selected as a parent. The step B, i.e. crossover, aims at combining the genetic information of the parents to generate new offspring. Initially, the algorithm defines a random value in the range 0–1, called *cross*, which is then compared to a value, called *pcross*, which corresponds to the probability of implementing a crossover operator and its value is set by the user. If the relation *cross* $<$ *pcross* is verified, the crossover process will occur. Therefore, the higher the value of *pcross*, the more strings generated will be the result of a genetic exchange. Several crossover operators exist: the most widespread as well as those applied in this study are the *one point* crossover, the *two point* crossover and the *uniform* crossover. The step C, i.e. mutation, is performed to maintain genetic diversity from one generation of a population of GA chromosomes to the next. The probability of occurrence of this operator is given by the value *pmut*. Traditionally, this variable assumes low values as it expresses the probability that errors can occurr during the genetic exchange. Therefore, for each allele, the system will define a random value in the range 0–1, called *mut*, which is compared to *pmut*. If the relation $mut \leq pmut$ is verified, the mutation operator will occur, i.e. the allele value changes from 0 to 1 and vice-versa. Once concluded the mutation phase, the evaluation of the generated strings occurs, i.e. step D. In particular, it is verified that each child satisfies all the model constraints: if even one constraint is not satisfied, the string is automatically discarded, otherwise the process moves toward the fitness function evaluation according to Eq. (1). The algorithm ends, i.e. step E, once a specific number of strings has been generated.

4 Case Study

In this section, a numeric operative case study is presented to evaluate the efficiency of the proposed model and its solving procedure. The instance considers the manufacturing of 5 products through a global set of 6 tasks. Moreover, the production environment includes 3 RMCs and 5 RMTs, i.e. RMT #1 and RMT #4 in RMC #1, RMT #2 in RMC #2 and RMT #3 and RMT #5 in RMC #3, while the equipment library has a set of 5 auxiliary module types. The compatibility matrix among tasks, RMTs and auxiliary modules is in Table 2.

Table 2. Compatibility data among tasks, RMTs and modules.

Tasks (o)	(Auxiliary modules) - [unitary processing times in minutes]				
	RMT #1	RMT #2	RMT #3	RMT #4	RMT #5
1	(1, 3) - [0.012]		(1) - [0.007]		
2		(1) - [0.01]			(1, 4) - [0.011]
3			(2, 5) - [0.008]		
4				(4) - [0.009]	(4, 5) - [0.009]
5		(2, 5) - [0.012]		(2, 5) - [0.011]	
6	(3, 4) - [0.007]				

This matrix shows the task execution modes, i.e. the RMT/RMTs needed for their processing, the required modules (in round brackets) and the unitary processing times (in squared brackets). Additional data about part work cycles, daily production volumes and auxiliary modules assembly and disassembly time are not detailed for the sake of brevity. Other relevant data concern the parameter *R*, set to a value equal to 6 units, and parameter *T* equal to 120 periods.

4.1 Genetic Algorithm Application

The GA algorithm used to solve and validate the proposed model is implemented in Microsoft Excel software using the Visual Basic for Applications (VBA) tool. The procedure starts with the generation of five parent strings considering the most relevant variable, i.e. W_{mit}, which specifies the RMT on which the part is located in each time period. Each parent has 3'000 binary values, i.e. 5 parts × 5 RMT × 120 time periods, and because of each part has to be processed by one RMT in each time period, 600 alleles of each string will take the value 1 while the remaining the value 0. Next Table 3 lists the five parents, satisfying all the model constraints, and their fitness value.

Table 3. Parent selection.

String	Fitness value [min]
Parent 1: W_{mit1}	10860.12
Parent 2: W_{mit2}	10826.18
Parent 3: W_{mit3}	10432.82
Parent 4: W_{mit4}	11556.42
Parent 5: W_{mit5}	9988.17

Once defined the parents, the algorithm selects two of them among the five available. Then, the crossover operator takes place, considering as values of *pcross* 0.90, 0.95 and 0.98 and the one point, two point and uniform as crossover operators. The mutation phase follows the crossover, performed setting as values of *pmut* 0.0002, 0.0001 and 0.002. Once these steps have been completed, the algorithm verifies that the two children satisfy the model constraints. In case of success, the child fitness is evaluated and it will be included in the set of the available parents. Finally, the algorithm checks whether the generated string is the hundredth, i.e. termination criterion: if not, it proceeds generating other offspring and repeating the process, otherwise it ends.

4.2 Experimental Results and Discussion

A multi-scenario analysis is performed varying, in each scenario, the crossover operator method and the *pcross* and *pmut* values according to the data discussed in Sect. 4.1, getting a total of 18 scenarios. Aggregated results are in next Fig. 2.

Results mark that the best scenario, in terms of lower fitness value, is the ID. 8, with a fitness value equal to 8995.91 min. Such scenario corresponds to the application of the two point crossover operator, while the selected *pcross* and *pmut* values are 0.95 and 0.0001, respectively. Conversely, the scenario characterized by the highest fitness is the ID. 1, with a fitness value equal to 12128.82 min. Such scenario corresponds to

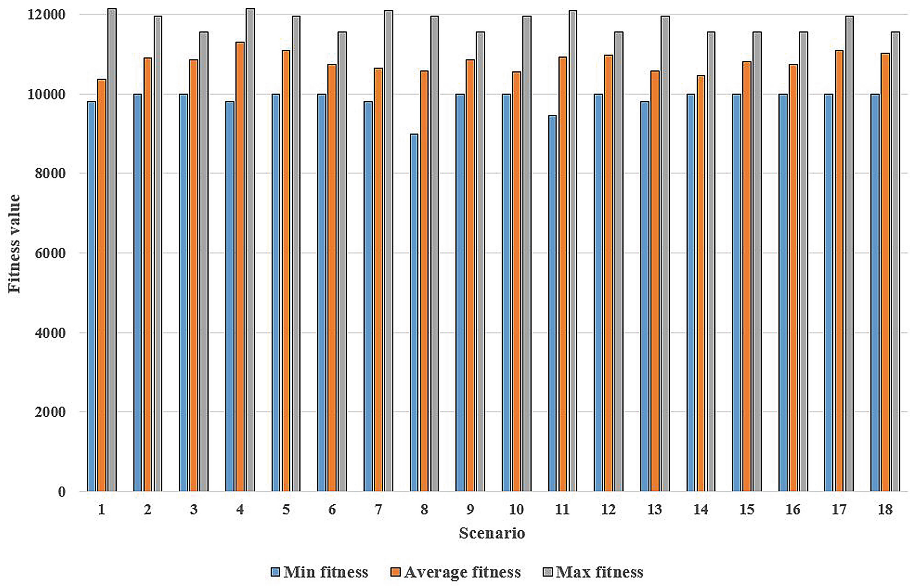

Fig. 2. Multi-scenario analysis results.

the application of the one point crossover operator, while the selected *pcross* and *pmut* values are 0.95 and 0.0002, respectively. Indeed, moving from such two scenarios, the fitness undergoes an increase of about 34%. Another relevant aspect to highlight is that the minimum and maximum fitness values are the same for all the scenarios in which the uniform crossover has been applied, i.e. scenario ID. 3, 6, 9, 12, 15, 18 with minimum fitness equal to 9988.17 min and max fitness equal to 11556.42 min. Moreover, such values correspond to the fitness of the parents. Therefore, the uniform method does not generate offspring with lower fitness values than the initial ones. Additional scenarios need to be assessed in the future, considering a wider set of *pcross* and *pmut* values as well as a more complex instance.

5 Conclusions and Future Research

In the last years, Reconfigurable Manufacturing Systems (RMS) emerged as an efficient manufacturing solution able to cope with the emerging industrial and market trends, e.g. dynamic market demand, short product life cycles, and flexible batches. To reach this goal, such systems use intelligent machines made by fixed modules and auxiliary custom modules, which can be assembled and disassembled when needed to provide different operational opportunities. In this scenario, this paper proposes a mathematical optimization model for the dynamic design of Cellular Reconfigurable Manufacturing Systems (CRMS) with the aim to best-balance the trade-off between the effort to reconfigure the manufacturing machine hosting the parts, in terms of auxiliary module assembly and disassembly, versus the inter-cell part travel flows. The model is, then, applied to an operative case study and solved by applying a genetic algorithm. Moreover, a multi-scenario analysis is performed applying different crossover operators, i.e. one point, two point and uniform, and different threshold values for the occurrence of crossover and mutation processes. Results from the considered instance highlight that the two point crossover operator allows achieving the lowest fitness value, i.e. the lowest value of the defined objective function. Future research deal with the inclusion of other relevant dimensions in the model formulation, e.g. economic, and the application of the model to larger instances.

References

1. Shou, Y., Li, Y., Park, Y.W., Kang, M.: The impact of product complexity and variety on supply chain integration. Int. J. Phys. Distrib. Logist. Manag. **47**(4), 297–317 (2017)
2. Bortolini, M., Galizia, F.G., Mora, C.: Reconfigurable manufacturing systems: literature review and research trend. J. Manuf. Syst. **49**, 93–106 (2018)
3. Mehrabi, M.G., Ulsoy, A.G., Koren, Y., Heytler, P.: Trends and perspectives in flexible and reconfigurable manufacturing systems. J. Intell. Manuf. **13**(2), 135–146 (2002). https://doi.org/10.1023/A:1014536330551
4. Koren, Y., Shpitalni, M.: Design of reconfigurable manufacturing systems. J. Manuf. Syst. **29**(4), 130–141 (2010)
5. Biswas, P., Kumar, S., Jain, V., Chandra, C.: Measuring supply chain reconfigurability using integrated and deterministic assessment models. J. Manuf. Syst. **52**, 172–183 (2019)
6. Molina, A., et al.: Next-generation manufacturing systems: key research issues in developing and integrating reconfigurable and intelligent machines. Int. J. Comput. Integr. Manuf. **18**(7), 525–536 (2005)
7. Esmaeilian, B., Behdad, S., Wang, B.: The evolution and future of manufacturing: a review. J. Manuf. Syst. **39**, 79–100 (2016)
8. Pattanaik, L.N., Jain, P.K., Mehta, N.K.: Cell formation in the presence of reconfigurable machines. Int. J. Adv. Manuf. Technol. **34**(3–4), 335–345 (2007). https://doi.org/10.1007/s00170-006-0592-5
9. Eguia, I., Molina, J.C., Lozano, S., Racero, J.: Cell design and multi-period machine loading in cellular reconfigurable manufacturing systems with alternative routing. Int. J. Prod. Res. **55**(10), 2775–2790 (2017)
10. Azevedo, M.M., Crispim, J.A., de Sousa, J.P.: A dynamic multi-objective approach for the reconfigurable multi-facility layout problem. J. Manuf. Syst. **42**, 140–152 (2017)
11. Ashraf, M., Hasan, F.: Configuration selection for a reconfigurable manufacturing flow line involving part production with operation constraints. Int. J. Adv. Manuf. Technol. **98**(5–8), 2137–2156 (2018). https://doi.org/10.1007/s00170-018-2361-7
12. Brahimi, N., Dolgui, A., Gurevsky, E., Yelles-Chaouche, A.R.: A literature review of optimization problems for reconfigurable manufacturing systems. IFAC-PapersOnLine **52**(13), 433–438 (2019)
13. Youssef, A.M.A., ElMaraghy, H.A.: Optimal configuration selection for reconfigurable manufacturing systems. Int. J. Flex. Manuf. Syst. **19**(2), 67–106 (2007). https://doi.org/10.1007/s10696-007-9020-x
14. Youssef, A.M., ElMaraghy, H.A.: Availability consideration in the optimal selection of multiple-aspect RMS configurations. Int. J. Prod. Res. **46**(21), 5849–5882 (2008)
15. Moghaddam, S.K., Houshmand, M., Fatahi Valilai, O.: Configuration design in scalable reconfigurable manufacturing systems (RMS); a case of single-product flow line (SPFL). Int. J. Prod. Res. **56**(11), 3932–3954 (2018)

16. Goyal, K.K., Jain, P.K., Jain, M.: Optimal configuration selection for reconfigurable manufacturing system using NSGA II and TOPSIS. Int. J. Prod. Res. **50**(15), 4175–4191 (2012)
17. Pattanaik, L.N., Kumar, V.: Multiple level of reconfiguration for robust cells formed using modular machines. Int. J. Ind. Syst. Eng. **5**, 424–441 (2010)
18. Bortolini, M., Galizia, F.G., Mora, C., Pilati, F.: Reconfigurability in cellular manufacturing systems: a design model and multi-scenario analysis. Int. J. Adv. Manuf. Technol. **104**(9–12), 4387–4397 (2019). https://doi.org/10.1007/s00170-019-04179-y
19. Eguia, I., Lozano, S., Racero, J., Guerrero, F.: Cell design and loading with alternative routing in cellular reconfigurable manufacturing systems. IFAC Proc. Vol. **46**(9), 1744–1749 (2013)
20. Eguia, I., Racero, J., Guerrero, F., Lozano, S.: Cell formation and scheduling of part families for reconfigurable cellular manufacturing systems using Tabu search. SIMULATION **89**, 1056–1072 (2013)
21. Bortolini, M., Ferrari, E., Galizia, F.G., Regattieri, A.: An optimization model for the dynamic management of cellular reconfigurable manufacturing systems under auxiliary module availability constraints. J. Manuf. Syst. **58**, 442–451 (2021)
22. Sivanandam, S.N., Deepa, S.N.: Genetic algorithms. In: Sivanandam, S.N., Deepa, S.N. (eds.) Introduction to genetic algorithms, pp. 15–37. Springer, Heidelberg (2008). https://doi.org/10.1007/978-3-540-73190-0_2

Industry 4.0 Technologies: A Cross-sector Industry-Based Analysis

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Abstract. The ongoing fourth industrial revolution, also known as Industry 4.0, was first introduced in 2011 at the Hannover Fair in Germany. Nowadays, such paradigm still represents a hot topic in the field of industrial engineering, with the aim to boot a radical transformation of the companies through the implementation of a set of new concepts and technologies, as Internet of Things (IoT), Augmented Reality (AR) and Big Data Analytics. Globally, companies all over the world expect to experience relevant benefits by implementing such emerging principles in terms of technical, economic, environmental and ergonomic performances. After providing a structured definition of the Industry 4.0 and a classification and description of its main enabling technologies, the aim of this paper is to perform a critical assessment about the Industry 4.0 principles implementation focusing on the three main transport sectors: automotive, aeronautical and railway, highlighting the most widespread technologies and the developed applications. The present paper provides valuable knowledge to support researchers and business practitioners in understanding the current implementation level of Industry 4.0 principles in the aforementioned sectors, supporting them in identifying the most compelling goals to be achieved in the near future.

Keywords: Industry 4.0 · Enabling technologies · Digital era · Sectoral analysis · Industrial revolution

1 Introduction

The concept of Industry 4.0 rose in 2011 in Germany as the fourth industrial revolution after the exhaustion of the previous ones. In particular, the first industrial revolution (1750–1870) increased the application of science to industry and led to the advent of mechanized production. The rise of electrical motors powered by electricity was the cause of the second industrial revolution (1870–1970), which led to the rise of mass production and large-scale manufacturing. The third industrial revolution (1970–2011) saw the development and deployment of Programmable Logic Controllers (PLC) and Information and Communication Technology (ICT) and led to production automation and human-controlled manufacturing. Finally, the fourth industrial revolution (2011-today) supports autonomous manufacturing and connected business and it is one of

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the most trending topics in both academic and professional fields, paving the way to a digital era by means of advanced and intelligent technologies, as Internet of Things (IoT), Augmented Reality (AR), Cyber Physical Systems (CPS) [1–3]. In such a way, the main components of a business or company are able to communicate in real-time and take decisions by continuously exchange data and information [4]. Such a digitization process allows the integration of systems and processes across companies and industrial sectors and, at the same time, it creates new business models and crucial opportunities for value generation. Moreover, this new industrial philosophy is influencing people's daily life in every aspect, from working to personal life because, in the Industry 4.0, factories, products and customers are becoming smart [5]. Current literature is full of surveys and literature review articles exploring the synergies between the emerging topic of Industry 4.0 and specific operations management areas and/or the achievement of a set of key performance indicators, e.g. impact of Industry 4.0 on sustainability, ergonomic, production, etc. While critical analysis assessing the current implementation level of Industry 4.0 principles and technologies in relevant business sectors are missing and expected. To fill this gap, after providing a structured definition of the Industry 4.0 and a classification and description of its main enabling technologies, the aim of this paper is to perform a critical assessment about the Industry 4.0 principles implementation focusing on the three main transport sectors: automotive, aeronautical and railway. According to this background and the outlined goals, the remainder of this paper is organized as follows: Sect. 2 presents a general overview of the Industry 4.0 paradigm and introduces and describes its main enabling technologies. Section 3 shows the critical analysis about the implementation level of Industry 4.0 principles in the automotive, aeronautical and railway sectors, presenting and discussing the most adopted technologies. Finally, Sect. 4 concludes the paper with final remarks and future research opportunities.

2 The Industry 4.0 and Its Enabling Technologies

Although the concept of Industry 4.0 generally refers to a strategic initiative to drive industry forward by enhancing digitization and the interconnection of products, value chains and business models, this concept is complex to define [6, 7]. The German digital association Bitkom supports this theory confirming the existence of more than 100 different definitions. Among the most acknowledged and accepted ones, Fact Sheet [8] defines Industry 4.0 as the integration of complex physical devices and machineries with networked sensors and software aiming to predict, control and plan for better business and societal outcomes. While according to Schumacher et al. [9], Industry 4.0 is a complex system encompassing a wide network of advanced technologies across the value chain, e.g. IoT, additive manufacturing, artificial intelligence, robotics, automation and service, which are leading to a new era of manufacturing processes. The boundaries between the real world and the virtual reality is getting thinner causing the rising of the so-called Cyber Physical Production Systems (CPPS). Wang et al. [10] propose another distinguishing definition for this fourth industrial revolution: a business stream that makes a full use of new technologies and rapid development of intelligent tools and machines to face global challenges to improve efficiency in industry. In such a way, the production can run faster with minimum downtime by integrating engineering knowledge, producing goods of increased quality. While all these definitions highlight that the advent and deployment of new technologies represent the core of this revolution, Fact Sheet [8] focuses the attention on the social outcomes derivable from this revolution. On the other hand, Schumacher et al. [9] and Wang et al. [10] stress that such a new industrial revolution is focused on manufacturing, acting to increase production efficiency by collecting smart data using advanced technologies and connecting machines, products and people. To achieve these goals, Industry 4.0 relies on a set of key enabling technologies. In next Subsect. 2.1, following the efforts made by past studies, such enabling technologies are collected into nine main categories.

2.1 Industry 4.0 Enabling Technologies

The Industry 4.0 enabling technologies are transversal applications, which foster accurate decision-making in real time, e.g. in the production processes or to pick up information [11, 12]. A deep analysis of the recent literature and industrial standard allows the identification of nine main enabling technologies, as in next Table 1.

Table 1. List and short description of the Industry 4.0 enabling technologies (ET).

ET name	ET description
1) Advanced manufacturing solutions	Autonomous and collaborative industrial robots Systems characterized by integrated sensors and standard interfaces
2) Additive manufacturing	Modern 3D printing techniques for prototypes and spare parts 3D facilities for inbound logistics, e.g. inventory, and outbound logistics, e.g. transport, optimization
3) Augmented reality	Augmented reality techniques and tools for production (manufacturing and assembly), logistics and maintenance Display of supporting information through e.g. smart glasses and advanced devices
4) Simulation	Simulation of value networks Digital twins of production systems
5) Horizontal/Vertical integration	Inter-company data integration Cross-company data integration
6) Industrial internet	Networks of products and machines Horizontal and vertical communications among all the production system components (product, machines, people)
7) Cloud	Management of big data volumes in open systems Real-time communication for production systems
8) Cyber-security	Defending computers, servers, networks and data from malicious attacks
9) Big Data and Analytics	Full evaluation of available data (from ERP, MES, etc.) Real-time decision-making support and optimization

All these technologies play a crucial role in managing the modern industrial and market complexity and contribute to foster digitization of business and processes [12].

Starting from this background, next Sect. 3 illustrates a critical analysis to assess the current level of implementation of such Industry 4.0 technologies into the three main transport sector, i.e. automotive, aeronautical and railway.

3 Industry 4.0 Implementation in the Transport Sectors: Automotive, Aeronautical and Railway

3.1 Automotive Sector

The automotive is a leading sector all over the world: global sales of cars amounted to about 64 million units in 2020, down from a pre-pandemic peak of about 80 million units in 2017. In the world panorama, China is considered one of the largest automobile market worldwide, both in terms of production and sales. However, while in the past car manufacturers offered a limited number of variants, e.g. according to Henry Ford's policy, in 1918 half of all cars in the US were model Ts, nowadays, due to the increasing market competitiveness, manufacturers need to provide a large product variety to meet customer requirements.

Analysing the current literature to assess the implementation level of the Industry 4.0 paradigm in this sector, although many papers propose reference framework for CPS-based automotive factors or to support technical maintenance in the context of cyber physical automotive production environment [13, 14], a wide set of papers propose innovative technologies and solutions derived from the ongoing fourth industrial revolution, to optimize the global automotive supply chain. A relevant issue explored by researchers and industrial practitioners is the car painting process. Colour gains the visual appeal and rises as a crucial purchase factor. In fact, according to PPG, about 60% of customers identifies colour as the major factor to consider in their car-buying decision. Figure 1 shows the 2020 Global Automotive colour popularity data, marking that the majority of cars are painted in the traditional colours of white, black, grey and silver.

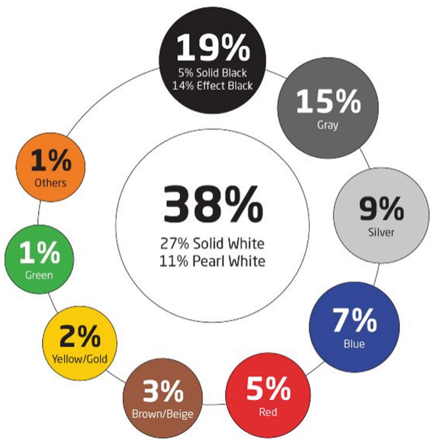

Fig. 1. 2020 global colour popularity (Axalta data).

In such a context, Bysko et al. [15, 16] focus on the research and development of a new paint shop concept for the automotive industry according to Industry 4.0 and the Digital Factory, in collaboration with a German car manufacturer. The main goal the project wants to achieve is to reduce bottlenecks during the operation of a paint shop, often caused by frequent changeovers of the painting guns. The method proposed by the Authors overcomes the limitations of the original Car Sequencing Problem, which focuses on determining the car sequence before starting production, preventing the possibility of later change to the established sequence. While the new algorithm, using Virtual Commissioning and Virtual Engineering, allows the real-time car sequencing introducing a buffer to consider dynamic changes. In addition, such virtual tools provide the possibility to perform detailed simulations in few time on standard computer, making possible including such simulations in the production preparation process and offline programming of the paint robots. In this way, a wide part of the production preparation process can be done in the computer. This allows car engineers to replace physical prototypes with virtual ones to reduce the product lead time, production cycle time and avoid technological and environmental problems. Another contribution is by Sanz et al. [17], which combine artificial intelligence and IoT to introduce predictive maintenance in the automotive paint shop process of the car manufacturer SEAT, which is part of the Volkswagen group.

A large number of Industry 4.0 applications in the automotive sector deals with the implementation of Augmented Reality (AR) techniques within the car assembly process. In fact, nowadays the efficient training of the operators is crucial because the complexity of the cars to develop is increasing. The widespread use of virtual prototyping in design tasks allows the availability of three-dimensional models for no additional costs, which can be reused thanks to AR technique for the training of employees. AR techniques allow achieving relevant benefits, e.g. more intuitive instructions compared to hand-written mode and they can show the instructed person how and where to perform the tasks directly on the training model. In this way, the learning time shortens since no mental transfer is needed and the instructed person can just see the instructions in front of his eyes. Furthermore, AR applications can be efficiently used to provide support to customers located all over the world. In this context, Vorraber et al. [18] perform a study in collaboration with AUDI using an AR-based technology, i.e. Microsoft HoloLens, and an audio-only communication system for remote maintenance. Hololens appear as promising devices due to their technical possibilities, e.g. marker-less tracking, immersive human-system interaction and hands-free operations. By implementing such technologies, employees experience time savings and increase in process efficiency. Lima et al. [19] perform a study in collaboration with Volkswagen to develop AR applications to track the location of 3D coordinates in a given automotive environment, which can be applied in many cars applications, e.g. maintenance assistant, intelligent manual. When performing such tasks, the mechanic is usually aided by precisely located augmented content with instructions, highlighting parts and illustrating what needs to be done in the current step (Fig. 2).

Fig. 2. AR applications for training and maintenance in the automotive domain [19].

In the Italian landscape, relevant Industry 4.0-based applications by car manufacturer, as Ferrari and Automobili Lamborghini, cover the areas of IoT solutions to improve maintenance operations and the introduction of collaborative robots to support employees in the whole car assembly process.

3.2 Aeronautical Sector

Every day, about 100,000 flights take off and land all over the world, moving about 6 million people, while 500,000 people are estimated to be in flight in every moment. Nevertheless, such trends are bound to increase. This means that, as for the automotive, the aeronautical/aviation sector needs to embrace new Industry 4.0-based methods and technologies powered by high-quality data to support the increasing traffic demand keeping, at the same time, airspace operations safe. Although the current literature about the implementation of Industry 4.0 principles in such a sector is poor, the existing studies prove that aerospace manufacturers are meanly investing in additive manufacturing (AM), i.e. 3D printing technology, and in AR applications [20, 21]. The reason lies in the fact that such technologies allows reducing the global aircraft weight by using innovative materials such as titanium. As reference example, in 2018, the French aerospace company STELIA developed a 1 sq. meter fuselage demonstrator with 3D printing, manufactured by a robotic tool, which should eliminate the current added stiffeners attached to the fuselage panels with fixing screws and welding. About the implementation of AR techniques, a relevant result in this field is achieved by Airbus company, which won the "Best Mobile Service or Solution for Enterprise" award in 2017 for being the first aircraft company in using a wearable technology based on smart glasses that allow the human operators to access to the data required to mark exact seating positions in aircrafts by entering a database located on a private cloud. Moreover, in the aeronautical sector, AR is successfully employed to assist air accident investigators, including both investigation activities and as a training resource [22]. In particular, AR is used to reproduce a real aircraft crash scene, both in terms of wreckage distribution and features of the surroundings, in a full-scale 3D environment (Fig. 3).

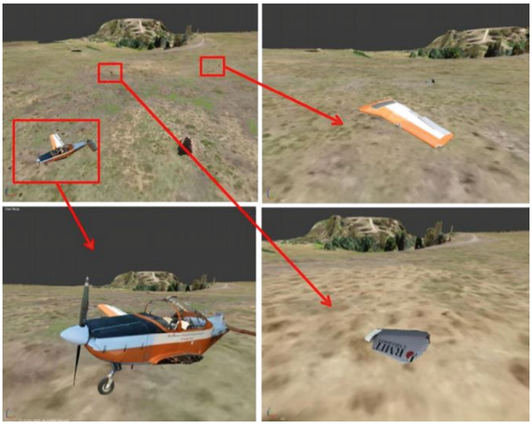

Fig. 3. 3D representation of the crash site [22].

Aerial photogrammetry using drones and low-cost laser scanner have been used to acquire data. Then, such 3D data are converted into an AR experience using low-cost commercial off-the-shelf products.

While Industry 4.0 enabling technologies as AR and AM found full application in the aeronautical sector, methods and tools based on the other enabling technologies, e.g. cyber security, industrial internet, are being developed and will be available in the near future.

3.3 Railway Sector

Similarly to the above described automotive and aeronautical sectors, the future of the railway industry will rely on smart transportation systems: new services as asset management, integrated security and predictive maintenance, are expected to improve passengers safety, scheduling and system capacity. This is a crucial goal to achieve because, according to the International Transport Forum of the Organization for Economic Co-operation and Development (OECD), by 2050, passenger mobility will increase by 200–300% and freight activity by 150–250% with respect to 2010 [23]. About the implementation level of Industry 4.0 technologies in this sector, one of the most relevant area concerns the inspection procedures on cargo trains. The company Rail Cargo Group chose the platform SPACE1, which combines AR and artificial intelligence to safely reducing risks for operators when performing routine inspections on cargo trains. In detail, such a solution allows technicians to perform their inspections hands-free simplifying the process for managing and sharing the know-how. Among the most relevant benefits, we can mention the development of standardized inspection procedures based on preset checklist and digital workflow, working in safe conditions thanks to AR and to a voice interaction device for performing tasks in hands-free mode, real-time compilation of digital reports and real-time support by experts. Such technologies for innovative inspections are also proposed by other studies [24], suggesting the use of tools as smart cameras and sensors. A second relevant area of investigation concerns the train maintenance [23, 24]. Among the most widespread technologies, Siemens inaugurated an innovative Rail Service Center, conceived as one of the most advanced train maintenance depots of its kind. All services are managed completely without paperwork. Moreover, the center also uses a 3D printer for producing plastic spare parts quickly and directly on site and the Automated Vehicle Inspection (AVI) system allows trains to enter the workshop and automatically undergo inspection of wheels, axles and tread patterns using the latest laser technology. Thanks to predictive maintenance strategies, Siemens guarantees availability of over 99%. A third area that is attracting the attention of researchers and industrial managers concerns the IoT for railway industry. In this field, one of the biggest challenges of railway maintenance is to generate knowledge from data and information. A relevant project in this area is IN2CLOUD [25], which aims to build an intelligent cloud with hybrid cloud learning and collaborative management to allow companies to learn from each other. IN2CLOUD will help the movement of railway industry systems from “local” to “global” optimization in a collaborative way thanks to shared information.

4 Conclusions and Future Research

The concept of Industry 4.0 emerged in 2011 as the fourth industrial revolution with the aim to drive industry and business companies towards a digital era. However, while many papers have been published performing surveys or literature reviews on the general topic of Industry 4.0, critical analysis assessing the current implementation level of Industry 4.0 principles and technologies in relevant business sectors are missing and expected. This paper fills this gap providing a structured definition of the Industry 4.0 paradigm and a description of its main enabling technologies. Moreover, it proposes a critical assessment about the Industry 4.0 principles implementation level into the three main transport sectors, i.e. automotive, aeronautical and railway, highlighting the most widespread technologies and the developed applications. Future research deal with the extension of this study to other relevant business sectors not explored at this stage, e.g. agriculture, shipping, etc.

References

1. Li, Y., Dai, J., Cui, L.: The impact of digital technologies on economic and environmental performance in the context of Industry 4.0: a moderated mediation model. Int. J. Prod. Econ. **229**, 107777 (2020)
2. Bortolini, M., Galizia, F.G., Mora, C.: Reconfigurable manufacturing systems: literature review and research trend. J. Manuf. Syst. **49**, 93–106 (2018)
3. Bortolini, M., Faccio, M., Galizia, F.G., Gamberi, M., Pilati, F.: Adaptive automation assembly systems in the Industry 4.0 era: a reference framework and full-scale prototype. Appl. Sci. **11**(3), 1256 (2021)
4. Chukalov, K.: Horizontal and vertical integration, as a requirement for cyber-physical systems in the context of Industry 4.0. Industry 4.0 **2**(4), 155–157 (2017)

5. Yuan, X.M.: Impact of Industry 4.0 on inventory systems and Optimization. In: Industry 4.0 – Impact on Intelligent Logistics and Manufacturing. IntechOpen (2020)
6. Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., Barbaray, R.: The industrial management of SMEs in the era of Industry 4.0. Int. J. Prod. Res. **56**(3), 1118–1136 (2018)
7. Raj, A., Dwivedi, G., Sharma, A., de Sousa Jabbour, A.B.L., Rajak, S.: Barriers to the adoption of Industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective. Int. J. Prod. Econ. **224**, 107546 (2020)
8. Consortium II. Fact Sheet (2013). http://www.iiconsortium.org/docs/IIC_FACT_SHEET.pdf
9. Schumacher, A., Erol, S., Sihn, W.: A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises. Procedia CIRP **52**, 161–166 (2016)
10. Wang, S., Wan, J., Li, D., Zhang, C.: Implementing smart factory of Industrie 4.0: an outlook. Int. J. Distrib. Sensor Networks **6**(2), 1–10 (2016)
11. Bigliardi, B., Bottani, E., Casella, G.: Enabling technologies, application areas and impact of Industry 4.0: a bibliographic analysis. Procedia Manuf. **42**, 322–326 (2020)
12. Wan, J., Cai, H., Zhou, K.: Industrie 4.0: enabling technologies. In: Proceedings of the IEEE International Conference on Intelligent Computing and Internet of Things, pp. 135–140. IEEE, Harbin (2010)
13. Weyer, S., Meyer, T., Ohmer, M., Gorecky, D., Zuhlke, D.: Future modeling and simulation of CPS-based factories: an example from the automotive industry. Ifac-PapersOnLine **49**(31), 97–102 (2016)
14. Juhász, J., Bányai, T.: What Industry 4.0 means for just-in-sequence supply in automotive industry? In: Jármai, K., Bolló, B. (eds.) VAE 2018. LNME, pp. 226–240. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-75677-6_19
15. Bysko, S., Krystek, J., Bysko, S.: Automotive paint shop 4.0. Comput. Ind. Eng. **139**, 105546 (2020)
16. Bysko, S., Krystek, J., Bysko, S., Lenort, R.: Buffer management in solving a real sequencing problem in the automotive industry-paint shop 4.0 concept. Arch. Control Sci. **29**, 507–527 (2019)
17. Sanz, E., Blesa, J., Puig, V.: BiDrac Industry 4.0 framework: application to an automotive paint shop process. Control Eng. Pract. **109**, 104757 (2021)
18. Vorraber, W., Gasser, J., Webb, H., Neubacher, D., Url, P.: Assessing augmented reality in production: remote-assisted maintenance with HoloLens. Procedia CIRP **88**, 139–144 (2020)
19. Lima, J.P., et al.: Markerless tracking system for augmented reality in the automotive industry. Expert Syst. Appl. **82**, 100–114 (2017)
20. Guyon, I., Amine, R., Tamayo, S., Fontane, F.: Analysis of the opportunities of Industry 4.0 in the aeronautical sector. In: 10th International Multi-Conference on Complexity, Informatics and Cybernetics (2019)
21. Ceruti, A., Marzocca, P., Liverani, A., Bil, C.: Maintenance in aeronautics in an Industry 4.0 context: the role of augmented reality and additive manufacturing. J. Comput. Des. Eng. **6**(4), 516–526 (2019)
22. D'Anniballe, A., Silva, J., Marzocca, P., Ceruti, A.: The role of augmented reality in air accident investigation and practitioner training. Reliab. Eng. Syst. Saf. **204**, 107149 (2020)
23. Fraga-Lamas, P., Fernandez-Carames, T.M., Castedo, L.: Towards the Internet of smart trains: a review on industrial IoT-connected railways. Sensors **17**(6), 1457 (2017)
24. Gerhatova, Z., Zitricky, V., Klapita, V.: Industry 4.0 implementation options in railway transport. Transp. Res. Procedia **53**, 23–30 (2021)
25. Lin, J.J., Kumar, U.: IN2CLOUD: a novel concept for collaborative management of big railway data. Front. Eng. Manag. **4**(4), 428–436 (2017)

Sustainable Purchasing Practices: A Study of Fresh Food SMEs in Yorkshire

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Abstract. This paper studies the sustainable purchasing practices of SMEs in the fresh food sector. Semi-structured interviews with farmers, retailers and wholesalers in five fresh food SMEs were supplemented by a survey questionnaire. Interview transcripts were analysed and interpreted using qualitative methods and the survey questionnaire responses were analysed using quantitative methods supported by MS Excel. The results are four-fold. First, owners' personal commitment on sustainability provides incentives for SMEs to implement sustainable purchasing practices. Second, brand reputation, pressures from consumers and government policies are important drivers underpinning the implementation of sustainable purchasing practices. Third, although most fresh food SMEs consider environmental and social factors to a good extent in their purchasing decisions, the lack of financial and human resources are the main barriers that affect their sustainable purchasing decisions. Fourth, most SMEs do not require certification from their suppliers, but they have strong relationships with small and independent suppliers and often monitor them regarding environmental and social issues. Some new insights on the frameworks typically used in sustainable purchasing practices are provided, e.g. the additional focus on fresh food SMEs, considering both drivers and barriers for the effective implementation of sustainable purchasing. Recommendations are provided, such as: purchasing managers should work more closely with their suppliers and local community on implementation of sustainable purchasing practices, and that fresh food SMEs require more financial and human resources in order to achieve effective sustainable purchasing practices.

Keywords: Sustainable purchasing · Fresh food sector · SMEs

1 Introduction

The aim of this paper is to investigate the sustainable supply chain management (SSCM) practices in the fresh food industry with a focus on SMEs based in Yorkshire (UK). Recent research has pointed out that UK adults deem sustainable practices as crucial, with 83% saying that retailers should reduce packaging, while free-range food products are the most widely bought food with ethical certifications, suggesting consumers consider animal welfare in their food purchases [1]. Thus, the following research question is examined: *How do small and medium enterprises (SMEs) in the fresh food sector in Yorkshire implement sustainable purchasing practices?*

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This paper is structured as follows. Section 2 covers a literature review on sustainable purchasing practices, as well as supplier evaluation and selection. In Sect. 3, the methodology is presented into two sections: qualitative and quantitative. Section 4 focuses on the findings on sustainable purchasing practices, drivers and barriers for their implementation. Section 5 presents a discussion of the key findings in relation to relevant literature and wider industry. Finally, Sect. 6 draws some conclusions and recommendations including some limitations and avenues for future research.

2 Literature Review

2.1 Sustainable Purchasing Practices

Purchasing is crucial in supply chain decision making, it can increase supply chain performance by fostering supplier collaboration and supplier development [2]. One of the main challenges to purchasing though is to integrate sustainability into the business. Sustainable purchasing considers the environmental, social and economic issues in the management of an organisation's external resources to supply goods or services for running, maintaining and managing the firm's activities to bring value to the organisation, society and economy [3]. Environmentally and socially sustainable business practices adopted by suppliers could be considerations for sourcing managers that influence their buying behaviours as well as the development of trust in the supply chain relationships [4]. However, purchasing managers are expected to source at the lowest possible price but they are often in a dilemma because they also need to consider which supplier performs the best from sustainable perspective [5].

A framework is proposed in [6] propose to analyse sustainable sourcing regarding the motives, processes and practices to answer the questions of "why, what and how". The main driver appears to be stakeholders' pressure [7], followed by compliance with standards, such as ISO14001 and ISO26000 [8]. Public image, competitive advantage [4] and consumer awareness and expectations [9] are also key incentives for sustainable purchasing. The processes consist of sustainable buying strategies, communication, supplier management, supplier assessment [10] and stakeholder collaboration [4].

Sustainable purchasing could be achieved through some practices such as supplier relationship management (SRM), supplier collaboration, supplier certification requirement [11] and supplier monitoring [12].

2.2 Supplier Evaluation and Selection

Supplier selection is a procedure to determine the most suitable provider to offer the highest quality products or service at a reasonable price at the right time [13]. It is the process of considering trade-offs among multiple criteria in decision making [14]. A balance of the short-term and long-term influences on the Triple Bottom Line (TBL), which includes environmental, economic and social dimensions of performance [15], is required in supplier selection decision [16]. Purchasing managers should consider more than the immediate buying decision based on the current requirement from a short-term point of view when selecting from multiple suppliers and the future and development of business should also be considered. Selection criteria and evaluation are the two most crucial activities while selecting a suitable supplier [17]. Purchasing managers should consider suppliers in terms of price, environmental aspects, and social responsibility performance to source from reliable suppliers [4]. For the sourcing strategy, single sourcing means that an organisation uses only one supply source for one specific material [18] while multiple sourcing appears to be more flexible and could provide alternative choices [19].

2.3 Food SMEs in the UK

Many SMEs find that there are strict government policies on sustainable issues, such as limits on chemical use and health and safety guidelines, which drives them to take environmental and social issues into consideration. However, due to the firm size, SMEs face financial resources and human resources restriction on implementing sustainable purchasing practices. SMEs may find it challenging to develop sustainability capabilities as they have less resources [20]. Moreover, SMEs face challenges in green initiatives adoption as they are unable to afford the development and to measure the performance of any initiatives after adoption [21].

3 Methodology

3.1 Qualitative Method

The interviews in this research were conducted with an organic food company, an ethical food company and three farm shops across Yorkshire, all of whom has between 10–249 employees. The interviews took place in Summer 2020. The participants from each company had all worked in the food industry for many years, and their role presently focused on either purchasing or sustainability. Each interview lasted between 20 to 30 min. However, interview samples selection may be constrained by the time available for the study, financial resources for travelling and other practical problems [23]. The profile of interviewees is shown in Table 1.

An interview protocol could be used to reduce the bias caused by distinct interviewers and participants to assists participants to answer questions suitably [22]. Interviewees were invited to answer the open-ended questions in the semi-structured interviews. An interview guide was provided, which was based on the literature review and previous research [24]. Before the interviews, the researcher briefly summarised the purpose of the research and sought the agreement of the interviewee to the interview procedure. Two interviews took place face to face, while three interviews were conducted over the phone, due to geographical distances and time restrictions. However, face-to-face interviews could facilitate access to views of interviewees and increase interactions [25]. Moreover, some verbal messages may have distinct meanings due to cultural differences, and it is important to focus on social conventions in a culture to understand the answers [26].

Table 1. Profile of interviewees

Company	Food sector	Location	Job title	Years in industry	Length of interview (mins.)
A	Organic food retailer	South Yorkshire	Sustainability director	25	30
B	Ethical food wholesaler	West Yorkshire	Purchasing manager	40	25
C	Farm shop and café	North Yorkshire	Purchasing manager	15	28
D	Farm shop and café	East Riding of Yorkshire	Retail manager	25	23
E	Farm shop and café	East Riding of Yorkshire	Managing director	28	24

3.2 Quantitative Method

The quantitative method could be used to analyse to what extent fresh food SMEs implement sustainable purchasing practice, and a survey questionnaire was used, with a five-point Likert scale. The survey questionnaires were distributed to fresh food SMEs within Yorkshire. They were distributed with a link generated from the survey tool Qualtrics and a formal explanation of the research project was sent to directors or purchasing managers (where applicable) in fresh food SMEs through email. The survey was carried out in parallel with the interviews in Summer 2020. Some of the interviewees agreed to fill in the follow up survey, which were then included in the sample.

4 Findings

4.1 Sustainable Purchasing Practices

Practices of sustainable purchasing include supplier selection and evaluation, factors considered for selection, auditing and monitoring processes. Some SMEs have systematic and formal supplier selection criteria and suppliers have to comply with the requirements to deliver their products to the buyers. For those companies which advocate certain types of food in its branding, they are more likely to have stricter and more formal supplier selection criteria in place. For example, there are systematic supplier selection criteria in the Company B including safe and hygienic working conditions and no discrimination. The company distributes the questionnaires regarding ethical trading to its suppliers to ensure they follow what the company policy is, and regulations require. Subsequently, the company selects suppliers according to the answers received from the questionnaires. However, some SMEs do not have formal supplier selection criteria in written and they source from local small suppliers or nearby farms as priority with the buying decisions being made based on the judgement of the purchasing managers themselves. Moreover, some managers evaluate their potential suppliers through site visits and discussions with suppliers in person. The sustainability director in Company A said that: *"I would go through selecting process on quality, price, service, financial stability and credit rate… make sure people from whom we are buying are resilient and maintain supply…require to be members of particular ethical trading organisation".*

In terms of auditing and monitoring processes, the practices were varied across the companies. Some companies required certifications from their suppliers instead of auditing by its own company, such as ISO14001, and the certifications need to be accredited by third-party bodies. *"The starting point must be the scheme, balancing between the benefits you would get and establish the relationship and the costs and risk being associated with before they start doing things right. There is no formal audit in our company but required a third-party accreditation scheme. Operational practices take environmental consideration…might expect to see something like ISO14001"* — Sustainability director in Company A.

In terms of social certification, *"We worked with Sedex and would audit them one to three year but if there is a problem would be more frequent"* stated the purchasing manager in Company B. Working with an external audit provider appears to allow better examinations and a deeper understanding of the performance of suppliers, which is because those service providers have knowledge and standards in place. Moreover, some SMEs choose to audit and monitor on their own, but some do not audit and simply trust what their suppliers say. "*Rely on our suppliers, we work with them because they have the same ethos as us and degree of trust, they know what we want and they are able to do that because that what they want, using trust more than certification"* (Company D). The farm shops that were interviewed did not have any formal audit or monitoring process of their suppliers, but they would support those in need. Their suppliers were trusted to ensure their products adhere to the minimum environmental and social standard. As the managing director of Company E said: *"Local suppliers on fresh produce line… have binding bond with them and I don't think we have issues with them. If I have, just speak with them but don't really need to audit".*

From the interviews across the five companies, the implementation of sustainable purchasing practices is varied. In terms of objectives and responsibility of purchasing, profit takes an important role in the buying decision process, although environmental and social issues in the food industry were raised amidst increasing awareness by the public and industry as a whole. Therefore, some firms implement sustainable purchasing practices, such as certification approval, auditing, and monitoring, although some businesses do not have any formal supplier selection criteria or auditing process, instead they rely on their suppliers' trust and also seek to support them when in need in a loose cooperative fashion.

4.2 Drivers and Barriers for Sustainable Purchasing Practices

In terms of drivers, government legislation, brand image and reputation as well as pressure from customers accounted for 22% each, whereas pressure from competitors accounted for 15% and personal reasons for 19%. In terms of barriers, financial resources accounted for 43% followed by human resources (29%) as main barriers when making purchasing decision considering sustainability, while sustainability information and related knowledge in sustainability have less impact on their decision making at 14% each. Only 25% SMEs have formal supplier selection criteria whilst six of them do not have. This indicates that most SMEs make purchasing decision based on the managers' own opinions or come to decisions after discussions within the team. The average score (classified as 1–2 = "Low", 3 = "Medium" and 4–5 = "High") in sustainability as whole is 3.67 and the average score of Triple Bottom Line (TBL) factors are: environmental = 3.5, social = 3.38 and economic = 4.13. This demonstrates that sustainability has been taken into consideration when making purchasing decision to a good extent, although economic factors would be more crucial than environmental and social factors. Moreover, price plays the most important role in decision making, followed by on-time delivery and supplier resilience (see Table 2). The third-highest scoring is food waste control, then the fourth-highest scoring is the use of local sourcing and recycled packaging. Purchasing managers work hard on food waste, local sourcing and using recycle packaging, which could have great impacts on environment and economy for both business and local community. However, most SMEs are less likely to choose to purchase organic food, although there are some SMEs who only source organic food to attract those customers who are willing to buy organic products.

Table 2. Triple Bottom Line (TBL) indicators [27]

Predominant TBL indicator	Average score
Economic: Price	4.25
Economic: On time delivery	3.88
Environmental: Food waste	3.75
Environmental: Local sourcing	3.63
Environmental: Recycle packaging	3.63
Economic: Supplier resilience	3.50
Social: Animal welfare	3.25
Social: Working conditions of suppliers	3.00
Environmental: Organic food	2.75

In terms of sustainable purchasing practices (see Table 3), the average score for environmental certificate and social certificate is the same at 3.5, which indicates that decision makers find it relatively important to require certificates from suppliers. Moreover, it is likely that decision makers seek to punish suppliers, such as search for alternatives if their suppliers act in a non-compliant manner for environmental or social issues, and they would disclose their supplier practices to the public to a moderate extent. However, they rarely engage with suppliers regarding sustainability issues and are less likely to provide feedback to suppliers in relations to sustainability practices. The survey result reflects that attitude towards organic food vary among SMEs.

In conclusion, data from the survey further evidence, economic factors as being the main driver for purchasing decisions, since price has the highest average score followed

Table 3. Sustainable purchasing practices

Sustainable purchasing practices	Average score
Environmental certification	3.50
Social certification	3.50
Punish suppliers	3.38
Disclose supply chain	3.25
Audit and monitor	3.00
Engage with suppliers	2.88
Feedback to suppliers	2.75

by that of on-time delivery. However, respondents are concerned about environmental and social elements. SMEs are thus likely to focus on dealing with food waste, local sourcing and recycled packaging, but organic food received a relative low rate in the results. In terms of sustainable purchasing practices, SMEs are more likely to require environmental or social certificates from suppliers and they would seek to punish suppliers, such as ending the business relationship, if there is no-compliance with the buyers' sustainability requirements. However, they are less likely to provide feedback and engage with suppliers regarding environmental or social problems.

5 Discussion

This paper addressed the research question: *How do small and medium enterprises (SMEs) in the fresh food sector in Yorkshire implement sustainable purchasing practices?* SMEs have awareness about implementing sustainable purchasing practices. However, the extent to which they implement those practices are varied across different types of companies. For example, a small company with ten employees has different resources and capabilities available than a company with 249 employees. SMEs that have invested in a particular food type, such as organic or ethical food, are better positioned to implement sustainable supply chain practices. This is because they have formal supplier selection criteria and are integrating sustainability requirement into their standard. The supplier selection process has become more complicated since it is not only considering price but also a series of factors which are crucial for the survival and future development of firms [28].

These companies advocating for certain types of food have a better understanding on sustainability and thus are more likely to apply stricter regulations or code of conducts when choosing their suppliers. For example, some companies required their suppliers to have third party accreditation, such as ISO14001 or organic label. There was no mention of the Sustainable Procurement standard, ISO 20400:2017. Auditing and monitoring ensure the compliance of standards, yet the SMEs did not audit on their own, but instead they worked with third party organisations, such as Sedex, to conduct procedural checks. Despite this, other SMEs did not have any formal supplier evaluation or selection standards and most purchasing practices were based on the purchasing managers' own judgement. In addition, buyers may find it difficult to measure environmental factors precisely as they are not allowed to access suppliers' information [29]. Therefore, the ability of managers to evaluate the performance of suppliers regarding sustainability is questionable since there are some measurements involved which is difficult to figure out through subjective judgment. However, this collaboration could facilitate trust between suppliers [30], which is likely to reduce the need to control the compliance of sustainability requirements from suppliers [31]. Those SMEs who do evaluate the performance of suppliers on their own, may only be requiring their suppliers to meet a basic standard in environmental and social terms. Trust and commitment are of great importance in the collaboration of two or more organisations. From the interviews, most suppliers of SMEs are small and independent suppliers, thus SMEs can work closely with their suppliers and provide help with those in need, which could enhance the buyer-supplier relationship, whilst the advice SMEs provide to suppliers could improve the service and overall performance of suppliers.

6 Conclusions

The results of this paper are summarised next. SMEs are highly influenced by their owners' personal commitment on sustainability. External factors such as brand reputation, pressures from consumers and government policies are important drivers for the implementation of sustainable purchasing practices. Most SMEs do not require certification from their suppliers, but they have strong relationships with small and independent suppliers and often monitor them regarding environmental and social issues The main barrier for implementation of sustainable purchasing is the lack of financial and human resources.

In terms of implications for practice. Firstly, it is necessary to require certification regarding environmental and social aspects from suppliers, if possible, because the official certification schemes could provide decision makers with more insights in terms of the environmental and social performance of suppliers which is difficult to examined and evaluated by the SMEs themselves. Secondly, local sourcing is beneficial to both companies and the local community. It could reduce carbon footprint to some extents and enhance the relationship with the local community. Furthermore, food waste frameworks are created by the researcher through analysis of the data from interviews with the farm shop which have both a café and a working farm. This demonstrates how SMEs could prevent food waste within their own company. This could therefore provide some ideas to managers in fresh food industry to take measures to better use the food waste, instead of it being wasted or disposed of.

Limitations of the research. Due to Covid-19, the responses to the survey questionnaire were limited, thus, the generalisability of the survey results are limited. Furthermore, interviews from five companies were conducted within Yorkshire alone, thus due to the geographic distance and time limitation, the results may not readily apply to SMEs in other locations. This means the results may not be generalisable to other regions in the UK, or to other sectors.

The study could be extended to other regions or use of other methodologies such as focus groups, secondary data and computer simulation. For sustainability practices, this study only focused on purchasing practices and future work should consider other worthy topics of research: sustainable packaging, relating resilience with sustainability, etc. Finally, future research can also investigate organisations operating in the same supply chain so that more in-depth understanding could be achieved.

References

1. Baker, A.: The Ethical Food Consumer. Mintel Report (2019). https://academic.mintel.com/display/920712/. Accessed 20 June 2021
2. Handfield, R.B., Monczka, R.M., Giunipero, L.C., Patterson, J.L.: Sourcing and Supply Chain Management, 5th edn. South-Western Cengage Learning, Boston, MA (2011)
3. Miemczyk, J., Johnsen, T., Macquet, M.: Sustainable purchasing and supply management: a structured literature review of definitions and measures at the dyad, chain and network levels. Surg. Endosc. Other Interv. Tech. **17**(5), 478–496 (2012)
4. Thomas, R.W., Fugate, B.S., Robinson, J.L., Tasçioglu, M.: The impact of environmental and social sustainability practices on sourcing behavior. Int. J. Phys. Distrib. Logist. Manag. **46**(5), 469–491 (2016)
5. Goebel, P., Reuter, C., Pibernik, R., Sichtmann, C.: The influence of ethical culture on supplier selection in the context of sustainable sourcing. Int. J. Prod. Econ. **140**(1), 7–17 (2012)
6. Ambekar, S., Kapoor, R., Prakash, A., Patyal, V.: Motives, processes and practices of sustainable sourcing: a literature review. J. Glob. Oper. Strategic Sourc. **12**(1), 2–41 (2019)
7. Wan Ahmad, W.N.K., de Brito, M.P., Tavasszy, L.A.: Sustainable supply chain management in the oil and gas industry: a review of corporate sustainability reporting practices. Benchmarking Int. J. **23**(6), 1423–1444 (2016)
8. Neumüller, C., Lasch, R., Kellner, F.: Integrating sustainability into strategic supplier portfolio selection. Manag. Decis. **54**(1), 194–221 (2016)
9. Giunipero, L.C., Hooker, R.E., Denslow, D.: Purchasing and supply management sustainability: drivers and barriers. J. Purch. Supply Manag. **18**(4), 258–269 (2012)
10. Frostenson, M., Prenkert, F.: Sustainable supply chain management when focal firms are complex: a network perspective. J. Clean. Prod. **107**, 85–94 (2015)
11. Busse, C., Schleper, M.C., Niu, M., Wagner, S.M.: Supplier development for sustainability: contextual barriers in global supply chains. Int. J. Phys. Distrib. Logist. Manag. **46**(5), 442–468 (2016)
12. Wright, C.F.: Leveraging reputational risk: Sustainable sourcing campaigns for improving labour standards in production networks. J. Bus. Ethics **137**(1), 195–210 (2016)
13. Dargi, A., Anjomshoae, A., Galankashi, M.R., Memari, A.: Supplier selection: a fuzzy-ANP approach. Procedia Comput. Sci. **31**, 691–700 (2014)
14. Amid, A., Ghodsypour, S.H., O'Brien, C.: A weighted additive fuzzy multiobjective model for the supplier selection problem under price breaks in a supply Chain. Int. J. Prod. Econ. **121**(2), 323–332 (2009)
15. Elkington, J.: Accounting for the triple bottom line. Meas. Bus. Excell. **2**(3), 18–22 (1998)
16. Wu, Z., Pagell, M.: Balancing priorities: decision-making in sustainable supply chain management. J. Oper. Manag. **29**(6), 577–590 (2011)
17. Polat, G., Eray, E., Bingol, B.N.: An integrated fuzzy MCGDM approach for supplier selection problem. J. Civ. Eng. Manag. **23**(7), 926–942 (2017)
18. Jia, F., Orzes, G., Orzes, G., Sartor, M., Sartor, M., Nassimbeni, G.: Global sourcing strategy and structure: towards a conceptual framework. Int. J. Oper. Prod. Manag. **37**(7), 840–864 (2017)

19. Tsai, W.C.: A dynamic sourcing strategy considering supply disruption risks. Int. J. Prod. Res. **54**(7), 2170–2184 (2016)
20. Fu, X., Zhu, Q., Sarkis, J.: Evaluating green supplier development programs at a telecommunications systems provider. Int. J. Prod. Econ. **140**(1), 357–367 (2012)
21. Mathiyazhagan, K., Govindan, K., Noorul Haq, A.: Pressure analysis for green supply chain management implementation in Indian industries using analytic hierarchy process. Int. J. Prod. Res. **52**(1), 188–202 (2014)
22. Yin, R.: Case Study Research: Design and Methods, 3rd edn. Sage Publications, Beverly Hills (2003)
23. Ghauri, P., Gronhaug, K.: Research Methods in Business Studies, 4th edn. Financial Times Prentice Hall, Harlow (2020)
24. Wolf, C., Seuring, S.: Environmental impacts as buying criteria for third party logistical services. Int. J. Phys. Distrib. Logist. Manag. **40**(1), 84–102 (2010)
25. Kvale, S.: Interviews: An Introduction to Qualitative Research Interviewing. Sage Publications, Thousand Oaks (1996)
26. Brinkmann, S., Kvale, S.: Interviews: Learning the Craft of Qualitative Market Research Interviewing, 3rd edn. Sage Publications, London (2015)
27. Pagell, M., Wu, Z., Wasserman, M.E.: Thinking differently about purchasing portfolios: an assessment of sustainable sourcing. J. Supply Chain Manag. **46**(1), 57–73 (2010)
28. Sen, D., Datta, S., Mahapatra, S.: Sustainable supplier selection in intuitionistic fuzzy environment: a decision-making perspective. Benchmarking Int. J. **25**(2), 545–574 (2018)
29. Roehrich, J., Hoejmose, S., Overland, V.: Driving green supply chain management performance through supplier selection and value internalisation: a self-determination theory perspective. Int. J. Oper. Prod. Manag. **37**(4), 489–509 (2017)
30. Gold, S., Seuring, S., Beske, P.: Sustainable supply chain management and inter-organizational resources: a literature review. Corp. Soc. Responsib. Environ. Manag. **17**(4), 230–245 (2010)
31. Kogg, B.: Responsibility in the Supply Chain: Interorganisational Management of Environmental and Social Aspects in the Supply Chain – Case Studies from the Textile Sector. Lund University, International Institute for Industrial Environmental Economics (2009)

Sustainable Manufacturing Digital Twins: A Review of Development and Application

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Abstract. Sustainable manufacturing as a concept as well as the practices that are deployed are well established in the literature. Tools that guide the development of manufacturing to have less environmental impact are being deployed and documented. The power of digital technology to enable manufacturing systems to be more productive is well established and advances continue to be made. What is less well known is how digital technology can support the pursuit of sustainable manufacturing, especially using digital models, shadows and twins. Here a digital simulation model is configured to analyse, replicate and drive the real production respectively to improve resource productivity in the widest sense. This paper considers the literature and practice of such digital tools in manufacturing operations as well as across the lifecycle. Literature considered is mostly from 2018 onwards as this is the point at which digital twin empirical work emerges. Whilst the work on digital twins is advancing fast, the work on sustainable manufacturing is limited to energy and, to some extent, resource efficiency. Further when compared to documented practice, the academic field appears to be lagging depending on how the loose definition of digital twins in practice is interpreted. The paper concludes with potential avenues for further research on digital models, shadows and twins in the pursuit of sustainable manufacturing.

Keywords: Digital twins · Sustainable manufacturing systems · Eco-efficiency · Industry 4.0 · Literature review

1 Introduction

Manufacturing is progressing towards sustainable production and consumption and the Sustainable Development Goals (SDGs) [1] through increasing resource efficiency [2] or potentially more significant changes in products and services [3]. Resource efficiency is considers energy [4], water [5] or other indirect consumption [6].

Lean tools and, increasingly, green tools have been deployed to realise improvements in resource efficiency [7]. More opportunities can be realized from wider scope [8] to account for energy and water flows as well as ancillary equipment, utilities and even the building itself. As the scope rises so does the need to incorporate more data.

Such analysis can be done offline to consider design or policy changes. To make operational changes to such as changes to production schedules, product routing, machine

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operating parameters, etc. then data needs to be analysed in real time [9]. Combined with the above scope, this means that analysis requires automated transfer of data from real systems to fast analysis models or tools [10].

Modelling, in particular simulation, is widely used to inform decision making in operations [11]. Such dynamic (time varying) analysis allows focus on raw materials, assemblies and finished products. Authors provide guidance on how to build models in general, e.g. [12] and when considering wider resources [13].

Simulation can be used to create three types of model: (1) offline digital model in which there is no automated data exchange between the digital and physical objects, (2) synchronised digital shadow that refers to a one-way data flow from the physical object to the digital object, (3) integrated digital twin in which a bidirectional data flow between the physical and digital objects exists [14].

There are many examples of offline digital models to support eco-efficient, sustainable manufacturing analysis, e.g. [15]. The term sustainable manufacturing here draws from earlier definitions [3, 8] that emphasis the environmental aspects including reduced consumption and waste as well as is open to the broader social considerations to include employee and wider societal impacts [41]. The latter is important in not confining digital twin application to automated systems alone.

The synchronization of models to create digital shadows to continuously replicate the real world have been around for decades [9] for traditional productivity analysis, however, it is only recently they have emerged with scope that includes environmental considerations. A crucial attribute of a shadow is that whilst it can be used to make decisions on changes to the real system operationally, such changes must be instigated through manual intervention as the data flow is one-way. Digital twins are synchronized models that can be used to enact changes autonomously in the real world, e.g. [16].

Digital or Industry 4.0 (I4.0) technologies enable such real-time monitoring and control of manufacturing systems by synchronizing the physical and digital worlds [16]. The digital twin is one core technology of I4.0 to optimize manufacturing performance.

Grieves [14] is one of the first to coin "digital twin" as the independent virtual representation of the real system. The twin duplicates the real system data through real-time communication throughout the lifecycle [17] of which the production stage is just one part. Crucially the twin can action changes in the real system to improve performance through autonomous decision making enabled by machine learning [17]. The continuous action of changes optimizes the real (physical) system to maintain the best performance. The question this paper addresses is to what extent are we currently able to optimize eco-efficient, sustainable manufacturing performance.

This paper seeks to guide future work on the application of digital twins in sustainable manufacturing systems by considering current knowledge in the academic and practice literature and identifying gaps for potential future research. The paper uses a structured literature review as well as a thematic practice review to establish such potential future research. The work considers the business and management literature to gain a picture of the types of digital representations (model, shadow and twin) across the lifecycle (from design to end of life) with a particular emphasis on manufacturing digital twins. Starting with the methodology, the literature is then detailed, discussed and conclusions made.

2 Literature Review

2.1 Methodology

A starting point for this literature review was to build on two key literature review papers published by Negri et al. in 2017 [16] and Kritzinger et al. in 2018 [18]. These works are comprehensive views from the traditional perspective of productivity rather than wider resource productivity. They give detailed definitions and classications of advances made and are therefore a baseline on which to build further review. In their search for digital twins, little that addressed sustainability even in the narrowest form was identified. For example, the focus on energy in passing [19]. Whilst these papers did not explicitly set out to focus on sustainability or environment, it is informative that a general search did not uncover examples. The following literature review therefore uses 2018 as the start point for digital twins and complements this with wider simulation and environmental and sustainable manufacturing papers from later general searches.

Scopus was used to identify literature using the keywords search string "(digital twin OR digital twins) AND (manufacturing OR manufacturing systems OR cyber physical production systems)". The search process led to 94 papers by limiting the search scope to the subject area 'Business, Management, and Accounting' and selecting papers in English published from 2018 to date (2021). Inclusion criteria also covered journal as well as conference papers to capture the latest developments. After applying exclusion criteria, 55 papers were used in the review. The exclusion criteria were: (1) "digital twin" phrase is used without bidirectional data flow between the physical and digital entities; (2) Industry 4.0 technologies proposals for which digital twins is not the focus.

2.2 Bibliographic Summary

Using the above generic search terms, resulted in papers that used a wider set of digital keywords (internet of things, smart, industry 4.0, data analytics, intelligent manufacturing, embedded systems) and more general keywords (life cycle, production system, manufacturing, production control, product design, decision making) for the context.

Certain journals and conferences dominate the field with the top four being (in order): International Journal of Production Research, IEEE International Conference on Industrial Engineering and Engineering Management, Journal of Cleaner Production and finally International Conference Management of Large-Scale System Development. There was an absence of papers from Operations Research journals.

Finally, it is interesting to note that the highest contributions came from (in order): China, Germany, Russia, Singapore, Italy then (jointly) Sweden and France.

2.3 Content Analysis

Whilst conceptual work dominated the pre-2018 digital twin literature, case studies make up just over half the latest literature showing a transition from the use of generalized data to that of real systems. However, most of these real systems are those in academic laboratories rather than commercial manufacturing systems.

The latest literature indicates a consensus on the definition of digital twins as distinct from digital models or digital shadows (for which definitions were presented earlier). The consensus on the lifecycle phases of digital twins is summarised in Table 1.

Table 1. Literature on digital twins for the lifecycle of manufacturing systems

Phase	Scope
Design	Product design as well as the production system design
Manufacturing	Production system and associated internal logistics
Service	Distribution, use, maintenance and repair
Retirement	Return, reuse, disassembly, remanufacture, disposal

Most papers focus on one phase. Table 2 summaries the distribution of the number of papers found (Qty) and a summary of the associated business outcomes sought.

For the design phase that includes the digital footprints of products examples include a twin to use big data to inform design decisions [20] and automated production system design [21]. The manufacturing phase dominated in this review given the search strings. Examples on real-time monitoring of the manufacturing process include a multi-fidelity method for a large-scale shop floor optimization [22] and sequencing and schedule optimization [23]. There were just two papers found that focused on both energy and resource planning, both were in energy-intensive operations [24, 25].

The service phase focuses on real-time operating state and providing predictive maintenance and fault diagnosis. It was the second most common application of digital twins after manufacturing. Examples of applications included investigating the remaining useful life of components [26] and end-to-end supply chain visibility [27].

Table 2. Literature on digital twins for the lifecycle of manufacturing systems

Phase	Qty	Business outcome
Design	8	Reducing design cost, reducing design cycle, increasing the geometrical quality of final product, improving product performance
Manufacturing	31	Reducing production cost, increasing production efficiency, increasing quality and throughput, reducing the geometrical deviations, reducing mean throughput time, increasing resource and energy efficiency
Service	15	Reducing maintenance cost, reducing bullwhip effect and ripple effect, increasing supply chain resilience
Retirement	2	Reducing the uncertainty in remanufacturing process, reducing electrical and electronics equipment waste

Few examples retrieved (as would be expected given the keywords used) focused the retirement phase. They covered the recovery and remanufacturing of WEEE (waste electrical and electronic equipment) [28] and tracking retired products [29].

When considering all phases together there was a dominance of production planning and control papers (30%), followed by product and process design (16%), maintenance (14%) and supply chain (11%). Many papers (18%) could not be given a specific classification in manufacturing and only a small number of paper (7%) address energy and resource planning. The remainder of papers (4%) addressed recovery and remanufacturing as to be expected from Table 2.

2.4 Focusing on Energy and Resource Planning

Four papers were identified as focusing on energy as well as wider resource planning. The papers were concerned with manufacturing phase in lifecycle of manufacturing systems only. They varied in the scope of model definition and interaction.

The virtual factories with knowledge-driven optimization [30] concept considered the mapping of models to decision making and the use of optimization techniques to reduce the computational burden in virtual commissioning. A robotic production cell model was constructed to consider cycle time and total energy consumption.

Next in the consideration of grinding in a shop floor, energy-efficiency decisions within energy-intensive manufacturing considers process settings and load shifting in multiple mills [25]. Capturing the resources delivered beyond the product raw materials, the system considers energy consumption against cost, energy and carbon metrics.

At the level of work centres, a digital twins considered production, costs and energy consumption [31]. Here creation, synchronization and utilization are considered as separate stages of the twin set up and use with emphasis on the data flows and their timing.

Finally, at a wider scope, in the examination of a plating process [24], the agent-based simulation model was integrated into a cyber physical production system (CPPS) to focus on resource planning incorporating water, air and, especially, energy. The metrics ranged from financial to energy to environmental impacts.

The examination of digital twins here shows that aspects of sustainable manufacturing can be considered. In examing production, there is a focus on energy with some consideration beyond to include water and air. Energy metrics (typically expressed as level, cost or carbon) are therefore the dominant metrics but there are case specific wider metrics. Overall, environmental considerations are of energy and flows of other resources. Wider sustainable manufacturing aspects receive limited consideration. Social sustainability [41] considerations were absent. The wider availability of generic frameworks could perhaps prompt wider metric and practice considerations.

The scope of the twins, perhaps due to the required data and computing power, are generally confined to one sub-system, cell or work centre within the firm. This potentially misses opportunities for improvements given that local optimizations are unlikely to result in system optimisations, i.e. at factory level or beyond. Further, none of those found considered lifecycle phases (as per Table 1) beyond manufacturing.

All works refer to a form of layering using terms multi-scale, multi-level and hierarchical. These refer to the configuration of the twin rather than levels of model abstraction. Hence the insight offered through focused high fidelity or opportunities from considering wider scope at (potentially) lower fidelity are absent. The challenge of how to move from machine model to production system model to supply chain model is unmet.

2.5 Wider Search on Sustainable Manufacturing

Given that the structured literature review search did not reveal significant literature on the application of digital twins for sustainable manufacturing, a wider specific search was conducted. It is known that simulation research has been carried out by many groups for sustainable manufacturing. Examples include energy consumption and scheduling [32], models of production, utilities and buildings [13] (but progressed by [24] above), the whole factory as a system [15] and production systems [33]. These are models and shadows rather than twins. The following additional works range from conceptual through to lab and to commercial production.

The system architecture or framework for intelligent sustainable manufacturing [34] presents a three-dimensional framework that incorporates life cycle phases, system level (device through to workshop to collaboration) and intelligent feature offer a potentially powerful guide to twin specification and implementation.

Extending the life cycle phase beyond manufacturing could be considered from ecodesign through to planning and monitoring manufacturing [35]. This work considers materials and methods selection as well as machining to impact on sustainability performance. Such integration of phases of design and manufacturing can be extended to incorporate service [36]. Again, energy features as a dominant sustainability dimension beyond the more typical manufacturing metrics. Interestingly, multi-granularity/scale is identified as one of the key challenges for twin construction and management along with minimizing the delay between real-time issue detection and its solution.

The issue of green material optimal selection in [36] is extended in the lifecycle thinking by including the retirement phase [37]. Here environmental as well as economic performance (energy, recycle waste, water pollution and emissions) can be considered through the phases of design, manufacturing, recycling and waste management. Whilst this is again conceptual, it demonstrates the breadth of digital twin scope potential for sustainable manufacturing considerations.

The work on smart manufacturing assembly [38] is of note for the fidelity within the manufacturing lifecycle phase. Whilst vague on the definition of sustainable manufacturing, the work considers material finish, assembly sequences and material handling. Whilst this is not obviously part of an integrated hierarchical model, it shows twins of levels within manufacturing that are typically considered independently.

Finally, the breadth of sustainability that considers social practices and impact by Ghobakhloo [41] was absent from digital twins research. Ghobakhloo focuses on I4.0 broadly rather than twins specifically, however, the work is informative for twins research extension.

In summary, acknowledging some papers found by this additional search are from research groups found in the structured literature review, application of sustainable manufacturing principles to the development of digital twins is possible and can be used to evaluate energy consumption and other environmental metrics across one or more lifecycle phases. There are still challenges and opportunities for the scope of models, the use of multi-level (multi-fidelity) models, integration of different types (machine, assembly, production system, etc.) of twins and achieving a comprehensive evaluation of environmental performance beyond energy and immediate shop floor focus.

3 Practice Review

This practice review seeks to verify whether the academic literature review is representative of practice therefore whether gaps identified earlier are valid. Given that industry reports and website information are not subject to peer review, the analysis below is to capture the language and activity rather form the basis for direct comparison. Company and product names are used to allow reference back to the company sources.

The adoption of digital in manufacturing is significant with many organisations planning or implementing digital twins [39] against a backdrop of market growth of 30% annually for the next 5 years [40].

Solutions are offered by manufacturers of digital hardware products (e.g. Bosch, General Electric, Nvidia, Siemens) and include product examples such as Eclipse Ditto, Mindsphere and Proficy. Their software provides twin functionality that integrates with their products. Solutions are also offered by software companies (e.g. Dassault Systèmes, IBM, IntelliSense.io, Lanner and Microsoft) and include products such as 3DEXPERIENCE, Brains.app, Digital Twin Exchange, Witness and Azure. These vary in their generality (e.g. Azure) to specific to manufacturing (e.g. Witness). They allow models, shadows and twins to be created through integration with existing business systems. For all solutions, there is an increasing use of machine learning (often expressed as Artificial Intelligence or AI) and analytics.

Reflecting on these commercial offerings, it is clear from the peer reviewed literature that research is lagging the reported commercial applications, e.g. the IntelliSense.io application to mining and manufacturing. Where enough detailed application is given, it is clear many commercial applications are digital twins and machine learning is in use, however, it is suspected that some applications labelled as such are really digital models or digital shadows. Available information on commercial applications typically lacks insight to the underlying framework and how the challenge of fidelity -vs- computation time is met. Most applications do not address environmental sustainability and any that do appear to focus on energy only. Social sustainability is again absent.

4 Discussion

This paper classified digital analysis by the level of data integration: (1) digital model created offline from the real world, (2) digital shadow with unidirectional automated data flow from real world to digital world, (3) digital twin in which data flow is bidirectional and synchronised [18]. Before 2018 studies belonged to the first two categories and limited studies on digital twin focused on conceptual, description treatment of the twin at various lifecycle phases. Since 2018 literature includes lab case studies or live production systems. The latter is poorly addressed in peer-reviewed literature, especially compared to applications from hardware and software solution providers.

Sustainability, especially environmental sustainability, receives little attention in the literature. What work there is typically addresses only on direct energy use by the production process, sometimes only in passing. The wider factory level energy use and, especially wider range of resources, is poorly addressed. There is often little insight to how energy for machines is modelled and what assumptions are made, for example, what is the energy consumption of an idle or standby machine.

Another area that receives little attention is model fidelity and scope, specifically how it is selected and what are the resulting assumptions. It is assumed that production system digital twins treat machines as 'black boxes' and requiring only the cycle time. This therefore misses understanding of how different types of twins can be integrated or how one twin could model multiple views of the same production system. For example, digital twins of machine tool operation and the wider production system are not considered together. Additionally, how do production systems twins relate to supply chain twins? Further work in this area could bring different twin research together. Also, high and low fidelity twins could be investigated for the value that they can bring in the accuracy of modelling and the number of experiments that could take place in the available time for robustness of decision making. One of the areas therefore for research is multi-level modelling. The literature references levels, hierarchy, etc. but the meaning and consistency of language means generalisation is difficult and perhaps misleading. Data analytics has potential for reduction in computation time for optimisation however generic or detailed frameworks are largely absent from the field.

There is a relationship between the research needs for sustainable manufacturing and the scope and fidelity of a digital twin. Machines do not only use energy and other resources whilst they are productive and they are not the only significant consumers of resources in a factory. Capturing a wider or higher fidelity view of the production system gives opportunities to address wider resource efficiency as well as optimise the whole system not just sub-systems. However, larger or more detailed models present greater computational burdens, hence ascertaining the impact of the scope and fidelity of a twin has potential for new knowledge for better practice application.

5 Concluding Remarks

This paper presents a review of digital twins with a particular focus on sustainable manufacturing. The review captured all lifecycle phases but focused on manufacturing phase and in particular progress in support of sustainability, especially environmental.

There has been some work on environmental sustainability, invariably focusing on energy consumption of the production machines. Further research on digital twins to develop more comprehensive models could provide opportunities to reduce environmental impact beyond the dominant focus on traditional narrower productivity metrics. Whilst there was a noted difference in the application of digital twins between research and commercial, the environmental impact does not feature strongly in either. Social sustainability consideration is absent.

In particular there appears to be opportunities to consider (1) the level of model fidelity, (2) the integration of modelling typically carried out by different types of twins, (3) the consideration of wider environmental metrics and the activities that influence them, (4) representative modelling of the energy, etc. consumers, (5) how the fidelity and scope of digital twin impact on production system (environmental) performance, (6) Social sustainability and the impact on other practices.

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References

1. UN: Transforming our world: the 2030 Agenda for Sustainable Development, A/RES/70/1, United Nations (2015)
2. Despeisse, M., Mbaye, F., Ball, P., Levers, A.: Emergence of sustainable manufacturing practices. Prod. Plan. Control **23**(5), 354–376 (2012)
3. Oliveira Neto, G.C., Lucato, W.C.: Production planning and control as a tool for eco-efficency improvement & environ. impact reduction. Prod. Plan. Control **27**(3), 148–156 (2016)
4. Dinçer, I., Zamfirescu, C.: Renewable-energy-based multigeneration systems. Int. J. Energy Res. **36**, 1403–1415 (2012)
5. Mousavi, S., Kara, S., Kornfeld, B.: A hierarchical framework for concurrent assessment of energy and water efficiency in manufacturing systems. J. Clean. Prod. **133**, 88–89 (2016)
6. Baker, M., Schaltegger, S.: Pragmatism and new directions in social and environmental accountability research. Account. Audit. Account. J. **28**(2), 263–294 (2015)
7. Yang, M.A., Hong, P., Modi, S.B.: Impact of lean manufacturing and environmental management on business performance: an empirical study of manufacturing firms. Int. J. Prod. Econ. **129**(2), 251–261 (2011)
8. Smith, L., Ball, P.: Steps towards sustainable manufacturing through modelling material, energy and waste flows. Int. J. Prod. Econ. **140**, 227–238 (2012)
9. Jackson, M., Johansson, C.: Real time discrete event simulation of a PCB production system for operational support. In: Proceedings of the Winter Simulation Conference (1997)
10. Reinhardt, H., Weber, M., Putz, M.: A survey on automatic model generation for material flow simulation in discrete manufacturing. Procedia CIRP **81**, 121–126 (2019)
11. Mourtzis, D.: Simulation in the design and operation of manufacturing systems: state of the art and new trends. Int. J. Prod. Res. **58**(7), 1927–1949 (2020)
12. Robinson, S.: The Practice of Model Development and Use. Red Globe Press, London (2014)
13. Herrman, C., Theide, S., Kara, S., Hesselbach, J.: Energy oriented simulation of manufacturing systems - concept and application. CIRP Ann. Manuf. Tech. **60**, 45–48 (2011)
14. Grieves, M.: Digital twin: manufacturing excellence through virtual factory replication. White Pap. **1**, 1–7 (2014)
15. Despeisse, M., Oates, M.R., Ball, P.D.: Sustainable manufacturing tactics and cross-functional factory modelling. J. Clean. Prod. **42**, 31–41 (2013)
16. Negri, E., Fumagalli, L., Macchi, M.: A review of the roles of digital twin in cps-based production systems. Procedia Manuf. **11**, 939–948 (2017)
17. Grieves, M., Vickers, J.: Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems. In: Kahlen, F.J., Flumerfelt, S., Alves, A. (eds.) Transdisciplinary Perspectives on Complex Systems, pp. 85–113. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-38756-7_4
18. Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W.: Digital Twin in manufacturing: categorical literature review and classification. IFAC-PapersOnLine **51**, 1016–1022 (2018)
19. Lindström, J., Larsson, H., Jonsson, M., Lejon, E.: Towards intelligent and sustainable production combining and integrating. CIRP Conf. Manuf. Syst. **63**, 443–448 (2017)
20. Tao, F., et al.: Digital twin-driven product design framework. Int. J. Prod. Res. **57**, 3935–3953 (2019)
21. Liu, Q., Zhang, H., Leng, J., Chen, X.: Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system. Int. J. Prod. Res. **57**, 3903–3919 (2019)
22. Zhang, Z., Guan, Z., Gong, Y., Luo, D., Yue, L.: Improved multi-fidelity simulation-based optimisation: application in a digital twin shop floor. Int. J. Prod. Res. 1–20 (2020)
23. Ding, K., Chan, F.T.S., Zhang, X., Zhou, G., Zhang, F.: Defining a digital twin-based cyber-physical production system for autonomous manufacturing in smart shop floors. Int. J. Prod. Res. **57**, 6315–6334 (2019)

24. Leiden, A., Herrmann, C., Thiede, S.: Cyber-physical production system approach for energy and resource efficient planning and operation of plating process chains. J. Clean. Prod. **280**, 125160 (2020)
25. Ma, S., Zhang, Y., Liu, Y., Yang, H., Lv, J., Ren, S.: Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries. J. Clean. Prod. **274**, 123–155 (2020)
26. Aivaliotis, P., Georgoulias, K., Arkouli, Z., Makris, S.: Methodology for enabling Digital Twin using advanced physics-based modelling in predictive maintenance. Procedia CIRP **81**, 417–422 (2019)
27. Ivanov, D., Dolgui, A., Das, A., Sokolov, B.: Digital supply chain twins: managing the ripple effect, resilience, and disruption risks by data-driven optimization, simulation, and visibility. In: Ivanov, D., Dolgui, A., Sokolov, B. (eds.) Handbook of ripple effects in the supply chain. ISORMS, vol. 276, pp. 309–332. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-14302-2_15
28. Wang, X.V., Wang, L.: Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0. Int. J. Prod. Res. **57**, 3892–3902 (2019)
29. Wang, Y., Wang, S., Yang, B., Zhu, L., Liu, F.: Big data driven Hierarchical Digital Twin Predictive Remanufacturing paradigm: architecture, control mechanism, application scenario and benefits. J. Clean. Prod. **248**(119299), 1–15 (2020)
30. Amos, H.C., Bandaru, S.: Virtual Factories with Knowledge-Driven Optimization as a New Research Profile (2020)
31. Park, K.T., Lee, D., Noh, S.D.: Operation procedures of a work-center-level digital twin for sustainable and smart manufacturing. Int. J. Prec. Eng. Manuf. Green Technol. **7**(3), 791–814 (2020). https://doi.org/10.1007/s40684-020-00227-1
32. Solding, P., Thallander, P.: Increased energy efficiency in a Swedish iron foundry through use of discrete event simulation. In: Proceedings of the Winter Simulation Conference (2006)
33. Jeong, Y., Flores-Garcia, E., Wiktorsson, M.: A design of digital twins for supporting decision-making in production logistics. In: Proceedngs of Winter Simulation Conference (2020)
34. He, B., Bai, K.-J.: Digital twin-based sustainable intelligent manufacturing a review. Adv. Manuf. **9**, 1–21 (2021)
35. Rojek, I., Mikołajewski, D., Dostatni, E.: Digital twins in product lifecycle for sustainability in manufacturing and maintenance. Appl. Sci. **11**(31), 1–19 (2021)
36. Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F.: Digital twin-driven product design, manufacturing and service with big data. Int. J. Adv. Manuf. Technol. **94**(9–12), 3563–3576 (2017). https://doi.org/10.1007/s00170-017-0233-1
37. Xiang, F., Zhang, Z., Zuo, Y., Tao, F.: Digital twin driven green material optimal-selection towards sustainable manufacturing. Procedia CIRP **8**, 1290–1294 (2019)
38. Židek, K., Pitel', J., Adámek, M., Lazorík, P., Hošovský, A.: Sustainability digital twin of experimental smart manufacturing assembly system for Industry 4.0 concept. Sustainability **12**(3658), 1–16 (2020)
39. Gartner Survey Reveals Digital Twins Are Entering Mainstream Use. https://www.gartner.com/en/newsroom/press-releases/2019-02-20-gartner-survey-reveals-digital-twins-are-entering-mai. Accessed 27 Apr 2021
40. Digital Twin Market Statistics | Global Size Forecasts 2026. https://www.gminsights.com/industry-analysis/digital-twin-market. Accessed 27 Apr 2021
41. Ghobakhloo, M.: Industry 4.0, digitization, and opportunities for sustainability, J. Clean. Prod. **252**, 119869 (2020)

Outlining the Limits of Friction Stir Consolidation as Used as an Aluminum Alloys Recycling Approach

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Abstract. Friction stir consolidation (FSC) is a solid-state process that recycles metal scraps economically and eco-friendly compared to the conventional melting method. The process parameters especially processing time and rotational speed, have a crucial role in achieving a sound disc during FSC. The current study answers the research question of how far these process parameters can be effective when the mass of chips to be recycled increases. In specific, an experimental setup was analyzed that was previously identified as challenging for recycling 20 g chips of aluminum alloy AA 2024-O. Rotational speed was set doubled, and processing time was increased up to 1.5 times of their initial values. The results were found opposing to the reported one. It was noticed that raising the processing time and rotational speed are not always promising to achieve a quality consolidated disc with better mechanical properties. In contrast, they can lead to unconsolidated discs with more non-homogeneous mechanical properties. Thus, this research work highlights the hidden challenges in producing a sound disc during friction stir consolidation.

Keywords: Friction stir consolidation · Recycling aluminum chips · Process parameters

1 Introduction

Aluminium production has increased rapidly over the last decades due to an increasing consumer population and new application areas of this versatile metal [1]. According to Hydro Annual Report, 2010 [2], the global aluminium consumption in 2019 was 89.9 million tonnes. In which the share for transport was 26%, 24% for construction, 11% for each of the categories electrical goods and machinery, 8% for each of the packaging and foil stock applications, and 6% for consumer durables.

However, the production of virgin aluminum from bauxite ore is a complicated process. It is costly, energy-intensive, and responsible for approximately 20% loss of pure aluminum. Besides, large amounts of waste slag are generated, which takes up considerable land resources and pollutes the environment [3]. Modern industrial societies and environmental policy efforts strongly encourage the processes that reduce primary resource use, pollution prevention, waste management, and sustainable products.

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Therefore, metals can be melted down, reformed, and reused without losing any of their beneficial qualities rather than mining for new ore. Such practices can meet much of the demand for new metals by simply recycling metals that are already in circulation. According to the European Aluminium Association (EAA, 2003), about 32% of European aluminium demand is satisfied by recycled material [4]. The quantities of recycled aluminium in Europe were estimated on 2.3 million tonnes approximately [5].

Usually, aluminum is recycled through the conventional melting method. However, this route has severe implications, especially during recycling aluminum scraps. It caused the adverse environmental impact, high cost, and significant material loss. Therefore, the research attempted solid-state recycling techniques [6–9]. These new methods can save up to 95% of energy, 59% of the cost, and 46% of material compared to the conventional melting process [10].

Duflou et al. [11] performed an environmental assessment of three different solid-state recycling methods comparing with the melting process as a reference. They concluded that solid-state recycling methods are more effective for machining scraps recycling. The kind of scraps, due to their high surface-to-volume ratio are prone to oxidation causing permanent material loss during the melting process.

Friction stir extrusion (FSE) is one of the solid-state methods used to convert metal scraps into the final product [12]. First, a rotating die plunges into a cylindrical chamber containing the metal scraps during FSE. Next, the stirring action of the tool plastically deforms the materials and forces them into the extrusion chamber. Finally, after densifying and heating, fully dense rods are extruded.

Many researchers have worked on the environmental assessment and finding the critical process parameters for FSE. Baffari et al. [13] analyzed the energy demand for 2050 aluminum alloy wire production through friction stir extrusion. They reported that FSE allows a reduction in energy demand up to 74% and 63% compared to the conventional and the equal channel angular process methods, respectively. Be-sides, growing extrusion rate or decreasing processing time led to reducing significant power demand was one of their critical findings.

Baffari et al. [14] investigated the effect of process parameters on friction stir extrusion of 2050 aluminum alloy. They found that high rotational speed and extrusion force caused significant grain growth and cracks due to high thermal input. Similarly, Tahmasbi et al. [15] analyzed the influence of rotational speed during friction stir extrusion of 7022 aluminum alloy. The study suggested that a rise in rotational speed decreased hardness and dislocation density and increased average grain size.

Friction stir consolidation (FSC) is a new solid-state process, similar to friction stir extrusion, differing for the absence of an extrusion channel within the tool. Further, a semi-product is developed in the form of a billet or disc shape that can be used for many applications. FSC process consists of two main steps: compaction and consolidation [16]. Compaction refers to the initial pressing of aluminum chips or powder in a hollow die chamber by applying a specific load through a cylindrical tool. The materials are then further pressed and stirred through the tool's downward force and rotational speed during consolidation.

Li et al. [17] revealed critical process parameters during FSC of AA 6061 aluminum alloy. They determined that increasing processing time, rotational speed, or consolidation force led to improved mechanical and metallurgical properties of the consolidated disc. Buffa et al. [18] examined the effect of processing time, rotational speed, and quantity of chips on the AA 2024 consolidated disc. The report suggested that increasing processing time and speed or lowering mass resulted in a better-quality consolidated disc.

In the current study, we extended our work on critical process parameters of FSC. Specifically, the mass of the chip was increased to 20 g, and the effectiveness of processing time and rotational speed were analyzed by using the experimental setup of the previous researcher [17, 18]. The aim was to analyze if, for challenging input chip masses (higher than 20 g), sound, as well as high quality, recycled samples can be obtained. The analyses were developed by increasing the main process parameters: the rotation speed and the consolidation time. The grain size, as well as hardness, were considered as the main output metrics. The study aims at improving the industrial applicability of the FSC process; as a matter of fact, bigger recycled samples would be beneficial both for FSC process productivity and for its environmental sustainability.

2 Materials and Methods

A cylindrical rod of 2024-O aluminum alloy was reduced to chips through turning operation (parameters listed in Table 1). The diameter of rod was 30 mm and chemical composition by mass percentage was 94.1Al-0.003-Cr-4.26Cu-0.57Fe-0.004Mg-0.01Mn-0.129Si-0.003Ti-0.008Zn-0.5Pb-0.12Sn. The chips were clean through acetone and then dried. Then a fixed mass of 20 g was charged in a die of 26 mm diameter (Fig. 1a). ESAB LEGIO, a dedicated friction welding machine and a cylindrical tool of 25 mm diameter (shown in Fig. 1b and c), were adopted to perform the experiments. A 5kN pre-load was applied to compact the charge, then followed by a consolidation force of 20 kN under the experimental conditions listed in Table 2 and Table 3.

Table 1. Detailed information of chips preparation

Machine	Process	Rotational speed (rev/min)	Depth of cut (mm)	Feed (mm/rev)	Cutting angle (degree)
COMEV 180	Finishing	460	1.5	2	15º

The consolidated disc was cut into two halves along the cylindrical axis. The disc section was well polished with water as a coolant and 0.05 μm alumina as a lubricant using a series of abrasive papers. Vickers hardness test was performed by applying a 49 N (5 kg) load for 15 s over the four lines along the cylindrical axis. The lines were at radius, r = 0 (central line), 6.50, 9.00, and 12.25 mm (near the external surface). The pitch of the load points was 0.50 mm, as shown in Fig. 2a. Specimens' microstructure was revealed through Keller reagent and then analyzed under the OLYMPUS GX51F microscope at a magnification lens of 5×, 20×, 40×, and 100×. On each line, grains were examined on three different zones (top, mid, and bottom), as shown in Fig. 2b.

Fig. 1. (a) Tool, (b) die & (c) ESAB LEGIO

Table 2. Experimental conditions

Constant parameter	Value of fixed parameter	Variable parameter	Level and value of variable parameter
Mass of charge (g)	20	Rotation speed (rev/min)	1000; 2000
Compaction force (kN)	5	Consolidation time (sec)	40; 60
Consolidation force (kN)	20		

Table 3. Experimental plan

Experiment no	Rotational speed (rev/min)-time (seconds)-mass (g)
Exp 1	1000-40-20
Exp 2	1000-60-20
Exp 3	2000-40-20
Exp 4	2000-60-20

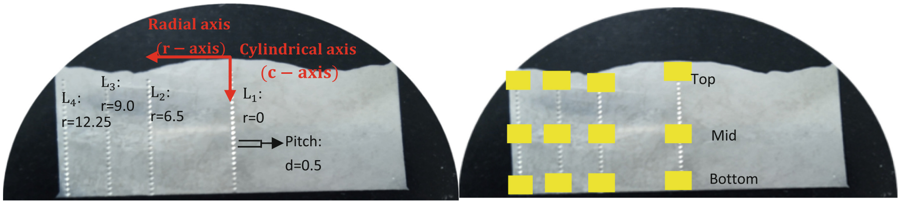
3 Analysis of Results

3.1 Grain Analysis

In this section, grains size has been analyzed along cylindrical and radial axes and its trend with processing time and rotational speed.

Grain Size Distribution Along Cylindrical Direction

A disc was developed at a rotational speed of 1000 revolutions per minute (rpm) and a processing time of 40 s during the first experiment (Exp 1). The disc section was examined



(a) (b)

Fig. 2. Schematic diagram for (a) Vickers hardness test (b) microstructure analysis **Note:** All dimensions are in mm for Vickers hardness test.

at the top, mid, and bottom zones to analyze grain size trends in the cylindrical axis. A zone of very refined grains was found at the top of the central line (Fig. 3a). Then, 1–2 mm below this zone, a grain growth occurred (Fig. 3b) until the mid of the disc section, where the grain size started to reduce (Fig. 3c). Finally, grains disappeared, and various defects originated at the bottom zone (Fig. 3d).

Grain Size Distribution Along Radial Direction

The other three lines at r = 6.50, 9.00, and 12.25 mm were also examined to analyze grain size trends in the radial direction. The zone near the top surface was characterized by coarse grains of the same size regardless of their distance from the central line (Fig. 4). At the middle of the disc, grains of larger size were observed on the central line. However, their size decreased continuously in the radial direction. In the bottom of the disc section, grains were not visible. Besides, the region with no visible grains expanded, and the number of defects increased from the central line towards the external surface.

Modelling of Grain and Defective Areas

Figure 5a depicts grain evolution during Exp 1. Based on the grain size distribution, the disc section has four major regions. In each region, the alignment of the grains is symmetrical along the cylindrical axis (central line).

The first zone represents an oval shape region at the top of the central line and is characterized by very refined grains. Then the second zone exists below zone 1. It is a rectangular-shaped area and composed of very coarse grains. In the third zone, grain size decreases continuously from top to bottom of the disc. Together zone 2 and zone 3 constitute a significant portion of the disc. Two triangular areas at the bottom represent the final zone. In this zone, grains started to disappear, and several defects emerged in the radial direction. Based on this model, roughly 25% sectional area of the disc was found defective (Fig. 5b).

Trend With Processing Time and Rotational Speed

For achieving a fully consolidated disc with uniform grain size, the consolidation time was increased from 40 to 60 s during Exp 2 while other parameters were kept constant. Nevertheless, the trend of grain size variation of Exp 2 was found similar to Exp 1, showing further grain growth in zone 2 due to the increased processing time (Fig. 6b).

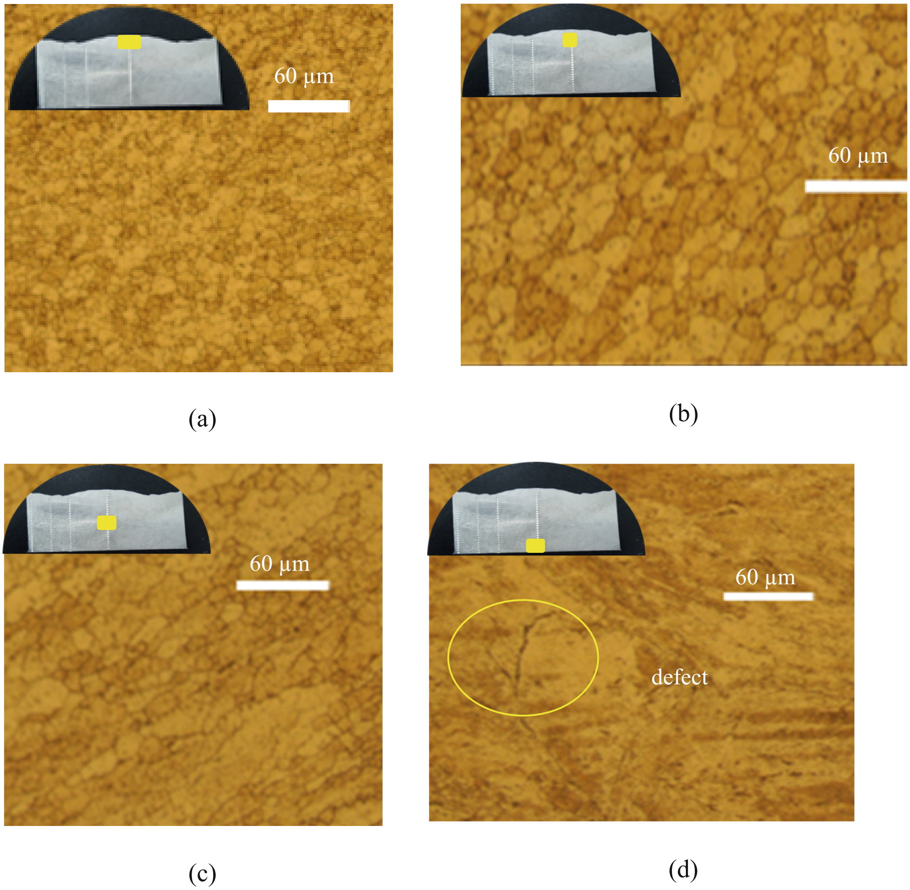
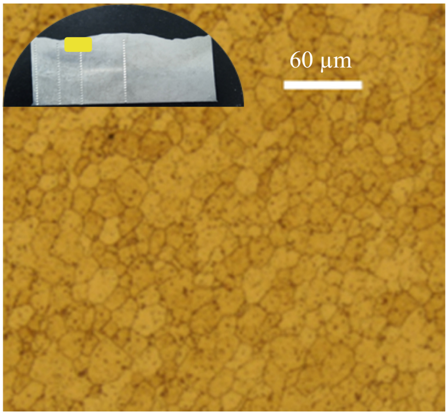


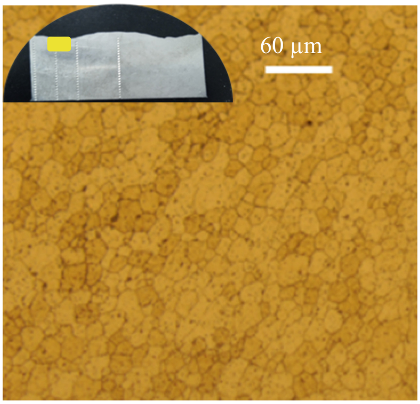
Fig. 3. Exp 1 central line at 20× (a) very top zone (c) zone near the top (c) mid zone and (d) bottom zone

Then in Exp 3, the rotational speed was doubled (from 1000 to 2000 rev/min). Once again, it caused grain growth in zone 2 (Fig. 6c) with no notable improvement in the quality of the disc. Finally, raising both processing time and rotational speed during Exp 4 caused no significant improvement in overall grain size distribution. However, it caused further grain growth in zone 2 (Fig. 6d).

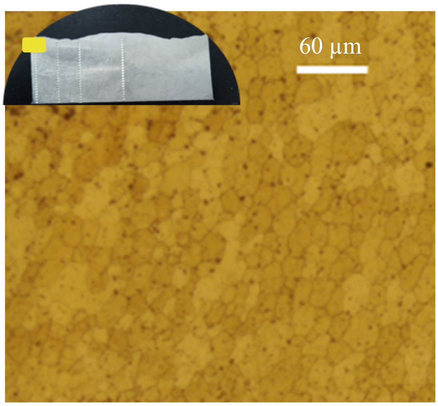
Even with 1.5 times rise in processing time and doubling rotational speed could not achieve a fully consolidated disc (Fig. 7). Both process parameters, though, lead to an increase in the average grain size. However, the increase in average grain size occurred mainly due to the grain growth at zone 2, while the grain size pattern at other zones remained unchanged. Thus, the standard deviation rose and intensified the non-uniform grain distribution across the disc section (Fig. 8).



(a)

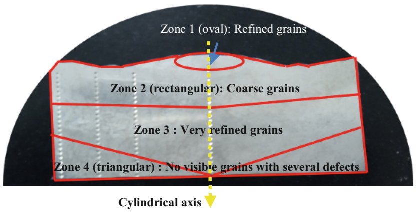


(b)

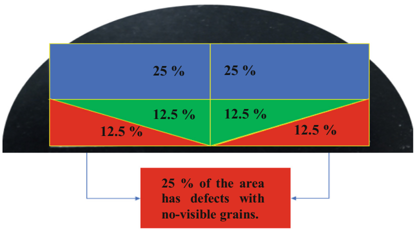


(c)

Fig. 4. Exp 1 top surface at 20× at lines (a) r = 6.5 mm (b) r = 9.0 mm and (c) r = 12.25 mm



(a)



(b)

Fig. 5. Scematic presentation of (a) grain evolution (b) area of visible grain

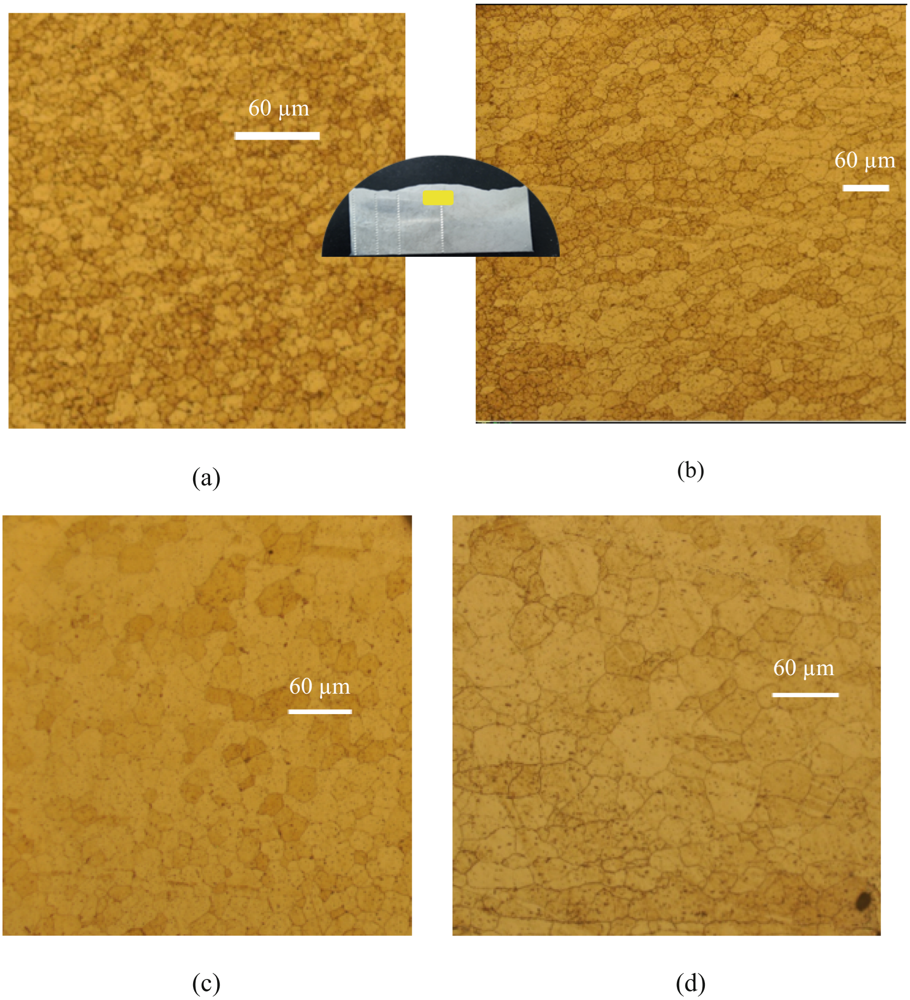


Fig. 6. Near the top surface of central line at 20× for (a) Exp 1, (b) Exp 2, (c) Exp 3, and (d) Exp 4

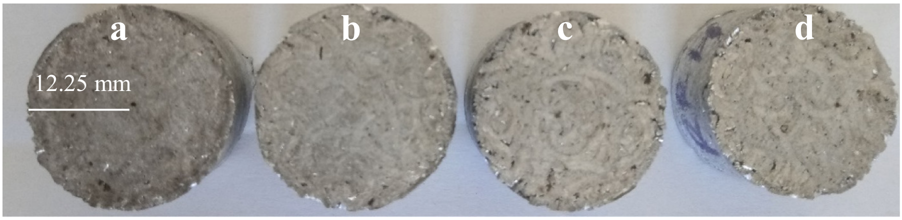


Fig. 7. Unconsolidated chips at the bottom of the disc (a) Exp 1, (b) Exp 2, (c) Exp 3, and (d) Exp 4

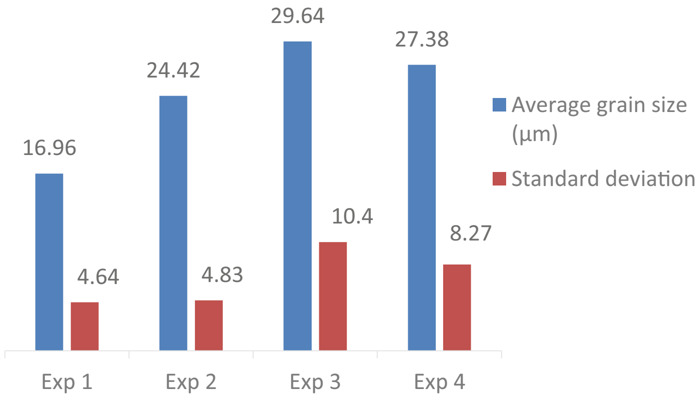


Fig. 8. Average grain size and standard deviation for all experiments

3.2 Hardness Analysis

This section provides a complete discussion about the trend of hardness along cylindrical and radial axes and influence of processing time and rotational speed.

Hardness Analysis Along Cylindrical Axis

The hardness value continuously decreases from top to bottom of the disc during Exp 1 (Fig. 9a) along the cylindrical axis. The maximum and minimum hardness values were existed at the top and bottom, respectively. The Vickers hardness value (HV) at the midsection was HV 58, almost equal to the average value. Besides, the lowest hardness values were observed near the surface at a line r = 12.25 mm.

Hardness Analysis Along Radial Axis

The hardness also follows a decreasing trend along the radial direction. It decreased from the central line to the line near the external surface. Although a uniform hardness of HV 50 was found at the bottom of the disc, this value is remarkably lower than the average hardness value (HV 58). Figure 9b provides a schematic presentation of hardness across the section of the disc during Exp1. Besides, symmetry also exits for hardness along the cylindrical axis (central line).

Effect of Processing Time and Rotational Speed on Hardness

The influence of processing time and rotational speed was analyzed by comparing the hardness of the central line. The trend of hardness was similar for all four experiments (Fig. 10). It was a decreasing trend both in the cylindrical and radial directions.

However, the processing time and rotational speed have no significant effect on the average hardness value, as shown in Fig. 11a. The average hardness was around HV 58. In comparison, the standard deviation of hardness values increased (Fig. 11b). This fact illustrates that increasing rotational speed and processing time result in more non-uniform hardness across the disc section.

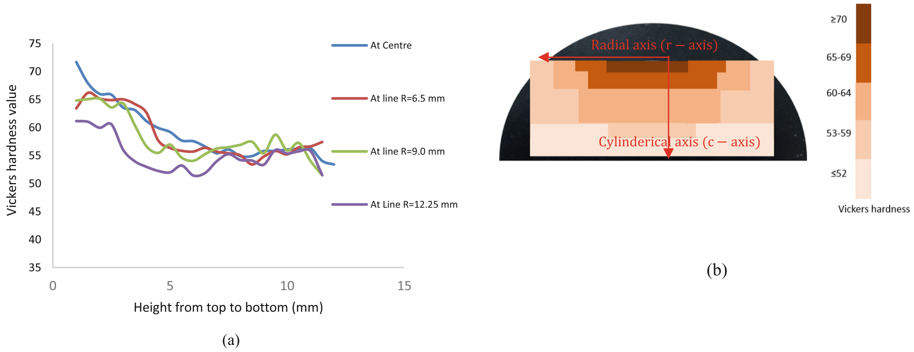


Fig. 9. (a) Hardness for Exp 1 over four lines and (b) schematic presentation for hardness profile

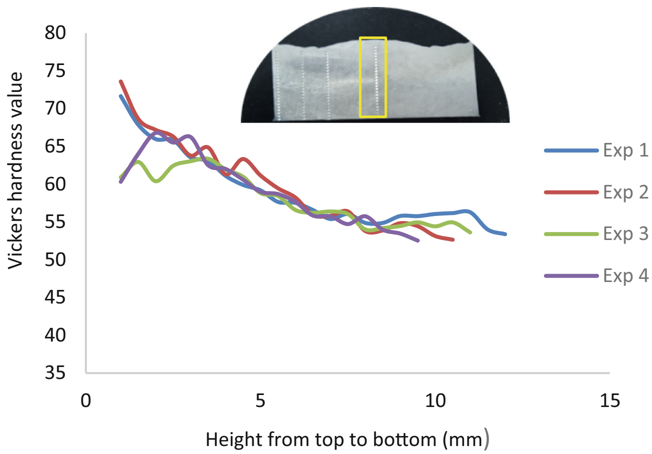


Fig. 10. Hardness over the central line for all four experiments

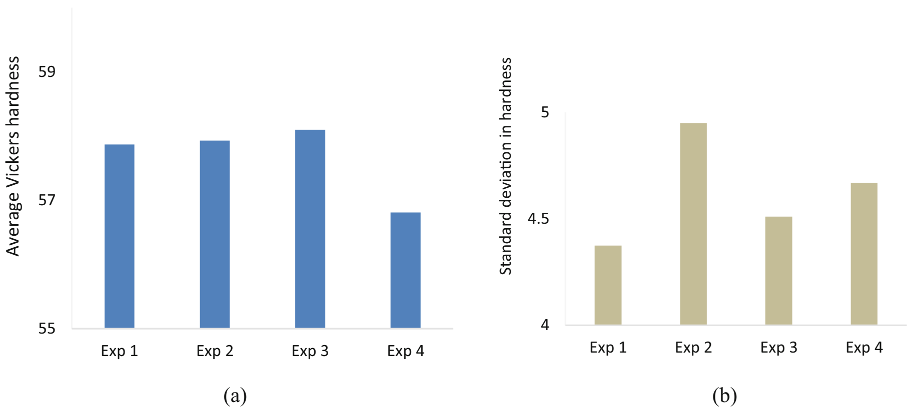


Fig. 11. (a) Average Vickers hardness and (b) standard deviation in Vickers hardness

4 Conclusion and Further Development

The rotational speed and processing time are the process parameters reported to improve the mechanical properties. Under the experimental setup of the current study, this fact is valid for recycling up to 15 g chips. However, when mass surpasses this threshold, these parameters become less effective to achieve a fully consolidated disc. In contrast, they intensify non-homogenous hardness value and grain size across the section of the disc. Based on the current study, the following main conclusions can be drawn.

1. Grain size distribution and hardness were found symmetrical along the cylindrical axis of the disc.
2. The processing time and rotational speed increased the average grain size, standard deviation and caused grain growth in the area closest to the top surface. On the other hand, the mid and bottom zones turned out to be unaffected and thus non-homogeneous grain size distribution intensified with increase in processing time and rotational speed.
3. Even 1.5 times rise in processing time, and double increment in rotational speed could not achieve a fully consolidated disc. Furthermore, defects like voids and cracks did not eliminate in the bottom zone.
4. Hardness value decreased both in the direction of cylindrical and radial axes across the section of the disc.
5. Average hardness value remained unchanged with increasing processing time and rotational speed. The standard deviation increased slightly and thus resulted in more non-homogeneous hardness across the disc section.

The study suggests that regulating mechanical properties by only varying process parameters is not adequate when recycling scrap mass exceeds 15 g for the experimental setup used in the current study. Therefore, strategies are to be identified to get a consistent grain structure and hardness value throughout the cross-section.

References

1. Gökelma, M., Vallejo-Olivares, A., Tranell, G.: Characteristic properties and recyclability of the aluminium fraction of MSWI bottom ash. Waste Manage. **130**, 65–73 (2021)
2. Hydro Annual Report: https://www.hydro.com/Document/Index?name=Annual%20report%202019%20web.pdf&id=506433 (2019)
3. Li, Q., et al.: Aluminum material flow analysis for production, consumption, and trade in China from 2008 to 2017. J. Clean. Prod. **296**, 126444 (2021)
4. European Aluminium Association (EAA): http://www.eaa.net (2003)
5. Organization of European Aluminium (OEA) Refiners and Remelters: http://www.oea-alurecycling.org (2004)
6. Wan, B., Chen, W., Lu, T., Liu, F., Jiang, Z., Mao, M.: Review of solid state recycling of aluminum chips. Resour. Conserv. Recycl. **125**, 37–47 (2017)
7. Haase, M., Tekkaya, A.E.: Recycling of aluminum chips by hot extrusion with subsequent cold extrusion. Procedia Eng. **81**, 652–657 (2014)

8. Behnagh, R.A., Fathi, F., Yeganeh, M., Paydar, M., Mohammad, M.A., Liao, Y.: Production of seamless tube from aluminum machining chips via double-step friction stir consolidation. Int. J. Adv. Manuf. Technol. **104**(9–12), 4769–4777 (2019). https://doi.org/10.1007/s00170-019-04326-5
9. Jordon, J.B., et al.: Direct recycling of machine chips through a novel solid-state additive manufacturing process. Mater. Des. **193**, 108850 (2020)
10. Samuel, M.: A new technique for recycling aluminium scrap. J. Mater. Process. Technol. **135**, 117–124 (2003)
11. Duflou, J.R., et al.: Environmental assessment of solid state recycling routes for aluminium alloys: can solid state processes significantly reduce the environmental impact of aluminium recycling? CIRP Ann. **64**(1), 37–40 (2015)
12. Behnagh, R.A., Mahdavinejad, R., Yavari, A., Abdollahi, M., Narvan, M.: Production of wire from AA7277 aluminum chips via friction-stir extrusion (FSE). Metall. Mater. Trans. B **45**(4), 1484–1489 (2014)
13. Baffari, D., Reynolds, A.P., Masnata, A., Fratini, L., Ingarao, G.: Friction stir extrusion to recycle aluminum alloys scraps: energy efficiency characterization. J. Manuf. Process. **43**, 63–69 (2019)
14. Baffari, D., Reynolds, A.P., Li, X., Fratini, L.: Influence of processing parameters and initial temper on friction stir extrusion of 2050 aluminum alloy. J. Manuf. Process. **28**, 319–325 (2017)
15. Tahmasbi, K., Mahmoodi, M.: Evaluation of microstructure and mechanical properties of aluminum AA7022 produced by friction stir extrusion. J. Manuf. Process. **32**, 151–159 (2018)
16. Baffari, D., Reynolds, A.P., Li, X., Fratini, L.: Bonding prediction in friction stir consolidation of aluminum alloys: a preliminary study. In: Fratini, L., Lorenzo, R.D., Buffa, G., Ingarao, G. (eds.) AIP Conference Proceedings 21st International ESAFORM Conference, vol. 1960, pp. 050002–050006. AIP Publishing LLC (2018)
17. Li, X., Baffari, D., Reynolds, A.P.: Friction stir consolidation of aluminum machining chips. Int. J. Adv. Manuf. Technol. **94**(5–8), 2031–2042 (2017). https://doi.org/10.1007/s00170-017-1016-4
18. Buffa, G., Baffari, D., Ingarao, G., Fratini, L.: Uncovering technological and environmental potentials of aluminum alloy scraps recycling through friction stir consolidation. Int. J. Precision Eng. Manuf. Green Technol. **7**(5), 955–964 (2020)

Sustainable Design of Takeout Product Service System of Milk Tea Drinks in Chinese University Campus Based on KANO Model

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Abstract. While milk tea drinks have gradually become the trend of consumption among young people, the consumption of disposable tableware such as milk tea cups and straws has brought great pressure to the environment. This study is aimed at Chinese university campus user groups. We first set up the product service system diagram, and clarified the relationships and interactions among the various stakeholders in the system. Then, we created the service blueprint and user journey, and used the Kano model to comb the user needs and the touch points of product and service system. Finally, we found the opportunities to optimize the system and explored the sustainable construction of the takeout product service system of milk tea drinks in Chinese university campus.

Keywords: Takeout product service system of milk tea drinks · Kano · Service blueprint · User journey · Sustainable

1 Subject Research Background

1.1 Demand and Market for Milk Tea

As a beverage for entertainment and leisure consumption, milk tea is popular in the market, especially with young consumers, for its fashionable and fast characteristics. In 2000, there were less than 1,000 milk tea companies across the country, and it has grown to more than 140,000 now. People's pursuit of milk tea has also been upgraded from the mainstream and fashion in restaurants and cafes to a composite experience of space, aesthetics, culture, and information exchange [1].

1.2 Consumption of Disposable Tableware of Milk Tea Products

The huge demand for milk tea brings about the consumption of a large number of disposable milk tea tableware, especially the consumption of milk tea cups. At present, the disposable plastic cups used in the market mainly include PE cup, PP cup and PET

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cup, while the more environmentally friendly milk tea shop will use paper cup. But in fact, the separation of the plastic coating and the paper cup, the removal of the ink and beverage residue on the paper cup, all bring great problems to the recycling of the paper cup. In addition, young people now drink milk tea more inclined to take out, resulting in a lot of milk tea cups cannot be found. Therefore, we will focus on the milk tea shops in Chinese universities and apply the sustainable product service system to it [2].

2 Research on the Status of the Existing Takeout Product Service System of Milk Tea Drinks

2.1 Product Service System

According to the general operating mode of the existing milk tea shop in the university, the following product service system diagram has been combed out [3].

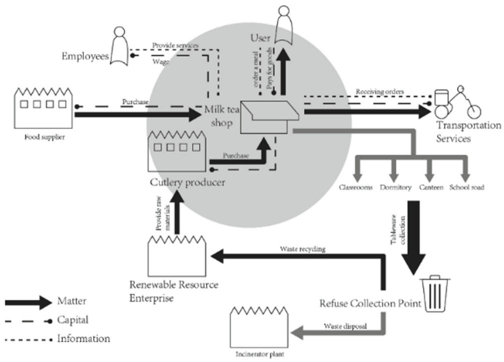

Fig. 1. Product service system diagram

Figure 1 clearly shows the relationship between various stakeholders, each link of the service, and the flow of material, capital, information and labor within it. Among them, the core stakeholders are milk tea shops, users and tableware producers.

2.2 Service Blueprint Based on User Journey Map

The service blueprint can clearly show the service process in the system, and visualize the emotions, satisfaction, expectations of users in each node of the service process, as well as the interaction of each component in the system [4]. We combined the user journey map and service blueprint to analyze the process of milk tea drinks industry providing services to consumers on university campuses.

Figure 2 and Fig. 3 are the service blueprints of consumers under online and offline ordering modes respectively. Figure 2 mainly shows that the waiting time is too long, the packaging quality and appearance affect the experience sense, and the post-meal waste disposal is inconvenient. In Fig. 3, the queuing time is too long, the environment of the

Stages	Preparation stage		Dining stage		Post dine stage
Physical contact	Mobile phones and other devices with ordering function		Catering & mobile phone	Catering	Waste tableware
User journey	Ordering by mobile phone	Waiting for meal	Take meal	Drinking	Handling disposable tableware
Ploblems	·Too many choices ·Quality is uncertain	·The waiting time is too long ·The quality of beverage is damaged during transportation	·There is a situation of someone else's drink by mistake ·Multiple plastic bags and disposable cups are used	·The quality of tableware affects the drinking experience	·Neither the cutlery nor the packaging can be reused ·Unclear waste classification
The phase that causes waste					
Opportunities	·The platform provides real user quality evaluation data	·Improve the production process ·The shopkeeper contacted the rider in advance	·Design distinct marks on the package ·Recycle cups ·Find alternatives to packaging	·Explore more comfortable tableware to use	·Prepare your own tableware ·Form a tableware recycling system
Front-end interaction	·Goods are displayed on the platform	·Shows whether the rider has received an order ·Show the rider's position	·Call / SMS for meal		·The cleaners came to collect the rubbish
Backstage support	·The merchant accepts the order ·Store update product information	·Making drinks ·The rider went to the store to pick up the meal ·Riders deliver meals	·The rider informs the customer to pick up the meal ·The rider delivers the meal to the designated place		·Incineration of non recyclable waste ·The recyclable garbage is sent to a special resource recycling plant for recycling
Tools	·Mobile phones ·Booking service platform		·Special electric vehicle for meal delivery ·Setting of takeaway store	·Tableware	·Recycling bins ·Plastic recycling technology and equipment

Fig. 2. Online ordering mode

Stages	Preparation stage		Dining stage		Post dine stage	
Physical contact	Ordering machine / reception	Tableware	Catering	Tableware & Packaging	Waste tableware	
User journey	Line up to order on site	Take meals	1 Eat in	2 Take it out to drink	Handling disposable tableware	
Problems	·There are many people in the queue and the waiting time is uncertain		·The tableware is disposable	·The drink was contaminated by the dust from the street ·The package is not sealed.	1 ·The clerk threw it directly into the garbage can ·Some stores will recycle for secondary use, but the cost is high.	2 ·Users throw it into the nearby garbage can
The phase that causes waste						
Opportunities	·Show the waiting time		·Reusable tableware can be provided	·Redesign the cup ·Reduce the drink's exposure to the atmosphere	·Design a cleaner and more transparent recycling system ·Limit the distribution range of such waste to facilitate recycling	
Front-end interaction	·Place orders at the self-service machine ·The clerk takes orders for customers	·The clerk prompted for your meal	·The store provides a relatively comfortable environment	·Provide disposable tableware ·Provide disposable plastic or paper bags	·The clerk threw it away	·The cleaner cleared away the rubbish
Backstage support	·Making meal	·Food preparation information link to the applet	·Shop assistants clean up regularly to ensure the hygiene and comfort of the dining area		·Incineration of non recyclable waste ·The recyclable garbage is sent to a special resource recycling plant	
Tools	·Self-service machines	·Applet	·Sanitary tableware	·Tableware	·Garbage cans for sorting and recycling ·Plastic recycling technology and equipment	

Fig. 3. Offline ordering mode

store needs to be improved, and the sealing, portability and pollution prevention of the packaging are not good enough.

Finally, we conducted a horizontal analysis of the service blueprint, and it was found that the waste mainly occurred in the dining stage and post dine stage. In the dining stage, customers were provided with disposable and non-recyclable tableware, whether they choose eat-in or take-out service, which leads to the consumption and waste of resources. In the post dine stage, the imperfect garbage sorting and recycling system and people's weak awareness of environmental protection have brought greater challenges to sustainable development.

2.3 KANO Model

Overview of KANO Model. Professor Noriaki Kano, from Tokyo University of Technology, established the KANO model for the first time in 1982, which can be used to analyze the impact of user demand on user satisfaction and present the relationship between user satisfaction and product quality. However, this model is only an auxiliary tool to study customer needs, providing theoretical guidance for product development and design, and cannot measure user satisfaction. It divides user requirements into five divisions, namely, basic needs, performance needs, attractions, indifference, and reverse needs [5] (Fig. 4).

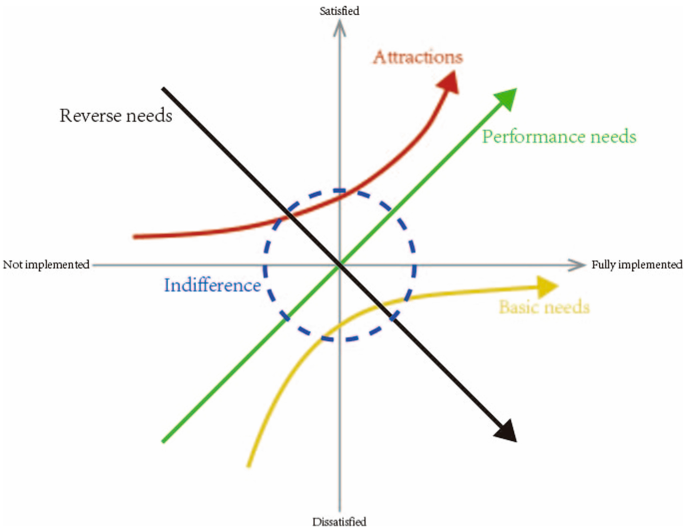

Fig. 4. Five divisions in KANO's model

User Requirements Analysis Based on KANO Model. Through literature review, observation, interview and summary of the service blueprint, we extracted the possible user needs and designed the questionnaire "Requirements of Milk Tea Drinks Consumption on Campus". Refers to the classified comparison table of Kano evaluation results, the questionnaire sets forward and reverse questions for each user needs to measure the user's response to the presence or absence of a quality feature [6]. We randomly distributed 350 questionnaires to different universities in China, and finally collected 317 valid questionnaires. In order to verify the credibility of the questionnaires, we divided all Chinese universities into three categories: technical university, undergraduate university and graduate university. Then, we randomly selected three samples from each university, and analyzed the information of the samples. As can be seen from Table 1, the sample distribution is relatively uniform, indicating that the questionnaires have a certain credibility (Tables 2, 3 and 4).

Table 1. AHP table

People		P1	P2	P3	P4	P5	P6	P7	P8	P9
Colleges	Technical university	√	√	√						
	Undergraduate university							√	√	√
	Graduate university				√	√	√			
Activities	Buy milk tea drinks online	√	√						√	
	Go to the shop to buy milk tea drinks			√		√	√	√		√
	Eat cakes from the milk tea shop				√					
Usage scenarios	Canteen							√		
	Dormitory								√	√
	On the campus road						√			
	Classroom	√	√							
	Milk tea shop			√	√					
	Other places					√				

Table 2. KANO evaluation result classification comparison table

Product/service demand		Negative (without this function)				
	Degree	I like it so much	It should be so	It doesn't matter	Accept reluctantly	I don't like it very much
Forward (with this function)	I like it so much	Q	A	A	A	O
	It should be so	R	I	I	I	M
	It doesn't matter	R	I	I	I	M
	Accept reluctantly	R	I	I	I	M
	I don't like it very much	R	R	R	R	Q

Table 3. Form of the questionnaire

Need	Degree				
	I like it so much	It should be so	It doesn't matter	Accept reluctantly	I don't like it very much
If the requirement A is met, what is your satisfaction?					
If the requirement A is not met, what is your satisfaction?					

In 1996, Berger proposed the Better-Worse coefficient. Quantify the user needs and user satisfaction from the effective questionnaires through the Better-Worse calculation formula. Put each need into the Better-Worse tetragonal potential coefficient analysis chart for data analysis and classification according to the absolute value of the Better-Worse coefficient.

$$\mathrm{Better/SI} = (\mathrm{A} + \mathrm{O})/(\mathrm{A} + \mathrm{O} + \mathrm{M} + \mathrm{I}) \tag{1}$$

$$\mathrm{Worse/DSI} = -1 * (\mathrm{O} + \mathrm{M})/(\mathrm{A} + \mathrm{O} + \mathrm{M} + \mathrm{I}) \tag{2}$$

SI indicates the degree of user satisfaction when the requirement is met, and its value is usually positive. The closer it is to 1, the greater the impact on user satisfaction will be. | DSI | indicates the degree of dissatisfaction of the user when the requirement is not met, its value is negative, usually the closer to 1, the greater the influence on user dissatisfaction. SI $>$ 0.5&DSI $>$ 0.5 is Performance needs; SI $>$ 0.5&DSI $<$ 0.5 is Attractions; SI $<$ 0.5&DSI $<$ 0.5 is Indifference; SI $<$ 0.5&DSI $>$ 0.5 is Basic needs [7].

In product optimization, the priority order of similar requirements is generally Basic needs > Performance needs > Attractions > Indifference. For similar requirements, the higher the SI, the higher the priority. Therefore, the overall priority order of user needs in the takeout product service system of milk tea drinks in Chinese university campus is: A1 > A6 > A8 > A14 > A13 > A7 > A12 > A15 > A4 > A5 > A10 > A3 > A16 > A9 > A11 > A2. We should ensure that Basic needs are met, Performance needs are satisfied as far as possible and appropriately meet the Attractions according to the business situation of the milk tea shop (Fig. 5).

Table 4. Analysis and category of user requirements

User demand	Num	A	O	M	I	R	Q	SI	|DSI|	Classification
Meal delivery reminder	A1	29	119	156	13	0	0	0.467	0.868	M
Personalized label on the cup	A2	151	33	35	98	0	0	0.580	0.215	A
Delivery on time	A3	29	143	130	15	0	0	0.523	0.861	O
The drink is of good quality	A4	42	174	93	8	0	0	0.681	0.842	O
The drink will not be polluted during drinking	A5	76	130	81	30	0	0	0.650	0.666	O
Easy to carry	A6	2	91	206	18	0	0	0.293	0.937	M
Shop environment	A7	99	131	56	31	0	0	0.726	0.590	O
Heat preservation	A8	16	55	233	13	0	0	0.224	0.909	M
Nice-looking package	A9	148	85	63	21	0	0	0.735	0.467	A
The package does not affect the taste	A10	11	179	88	39	0	0	0.599	0.842	O
Drinks in moderation	A11	134	64	88	31	0	0	0.625	0.479	A
It's not easy to leak	A12	21	198	79	29	0	0	0.691	0.874	O
Safe material	A13	2	21	289	5	0	0	0.073	0.978	M
Easy to hold in one hand	A14	19	45	226	27	0	0	0.202	0.855	M
The cup is insulated	A15	15	203	80	19	0	0	0.688	0.893	O
It can be customized according to customers	A16	177	69	57	14	0	0	0.766	0.397	A

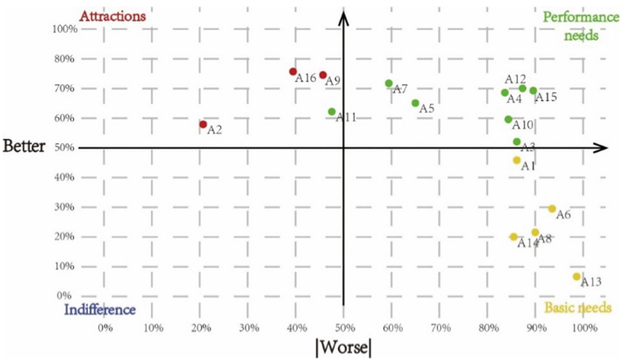

Fig. 5. Better-worse tetragonal potential coefficient analysis chart

3 Design Concepts About Sustainability

3.1 Sustainable Development Theory

In 2007, Munasinghe put forward the theory of "Sustainable Development Triangle" [8], which understands Sustainable Development from three dimensions: economy, environment and society. At the economic level, sustainable development implies a strong resilience of the economic system. On the environmental level, emphasis is placed on maintaining the resilience of the ecosystem. At the social level, ethics and fairness should be emphasized to enhance the vitality of social and cultural systems.

3.2 Sustainable Development Applications

Traditional products mostly focus on the function, appearance and durability of the product, but the requirements of sustainable development of the product will pay more attention to energy consumption, impact on the environment and the end-of-product life cycle management [9]. The key to applying sustainable development to the system is to clarify the interaction between various stakeholders in the system and transform the products sold into sales experience and make users and enterprises reach a consensus and tend to sustainable development consciously.

According to the system diagram analyzed above, we try to nest the interests of each member into the service process to make their behavior more sustainable.

3.3 Sustainable Design Concepts

Based on the above analyses, we decided to use reusable cups made of wheat straw and straw made of disposable degradable straw, and proposed three design concepts (Fig. 6):

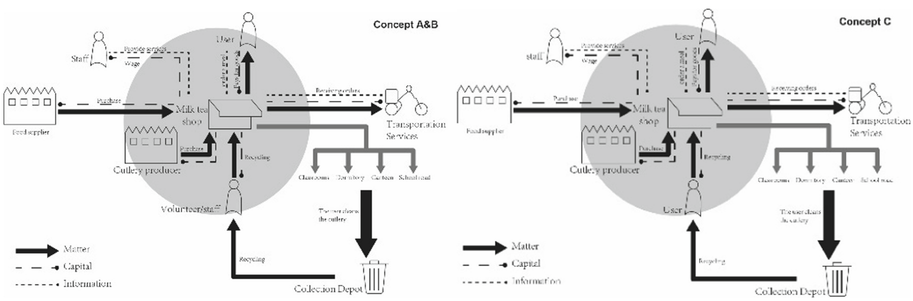

Fig. 6. System diagram of concept A, B and C

a. Milk tea shop staff or volunteers to clean recycled tableware.
b. Set up automatic cleaning machines. The staff only needs to go to the cleaning machines regularly to retrieve the tableware to the store.

c. After drinking, the user cleans the cup and places it at the nearby recycling point. Each user must place a clean cup in it to get a new one. Users who bring cups to the shop can enjoy a discount.

The system diagrams of concept A and B are structurally similar. However, the automatic cleaning machine in concept B requires the investment of the milk tea shop, which is not economical. Concept C encourages users to recycle tableware through store preferential treatment, and then makes up for the reduced profit of it with reducing tableware consumption, so as to balance the interests of merchants and consumers. In conclusion, concept C seems more in line with the requirements of sustainability.

4 Design Practice

4.1 Determination of the Concept of the Beverage Cup

Fig. 7. Final design of the cup

The final design of the cup is determined according to the previous researches. Its shape and color are for reference only. The cup is made of insulated straw material that meets A8, A13, A10 and A15. The cups are designed in two sizes. Users can choose different sizes of cups according to their own needs, which meets A11. The small cup capacity is 350ml, the maximum diameter is 80 mm, the minimum diameter is 60 mm; The large cup has a capacity of 500 ml, with a maximum diameter of 90 mm and a minimum diameter of 55 mm. Suitable for most adults with one hand grip, meets A14. The top cover of the cup is opened in an upward way, which is convenient for users to drink milk tea while walking. After drinking, the top cover can be closed to prevent air pollution. They meet the requirements of A6, A5 and A12. Sliders on the cover provide a customized service for temperature and sweetness, meets A16 (Fig. 7).

4.2 Service Process Design Practice

To comply with the development of the data era and the trend of online operation, we will implant WeChat applet into the product service system. It will serve as a tool for verifying the identity in the process of ordering food and recycling to provide users with more convenient services. In the process of ordering meals, the applet provides functions such as selecting commodities, online payment, displaying the waiting time, reminding to take meals, etc. In the process of recycling, users can take and place the cups by identifying the QR code on the machine to complete identity verification. The user who chooses “Bring my own tableware” in the applet can get the discount.

5 Summary and Prospect

In this paper, system diagram, service blueprint, Kano model and other tools are used to study the sustainability and optimal design the takeout product service system of milk tea drinks in Chinese university campus. The final design meets the requirements of sustainable development from three dimensions: economic, social and environmental. On the economic level, the recycling of milk tea cups reduces the cost of milk tea products, increases the profit of milk tea shops and reduces consumer spending. On a social level, the design of milk tea cup makes it easier for the clerks to work. The customer's involvement in the recycling process raises awareness of sustainability and eases the work of the shop assistants. At the environmental level, giving up the use of disposable and non-recyclable tableware reduces the consumption and waste of resources and eases the environmental burden. By adjusting the interaction of the participants in the system, the design can arouse their enthusiasm to participate in environmental protection and provide a new idea for building a virtuous cycle of sustainable system. However, the application scope of this system is limited to the campus. If it is to be applied to the whole society, the sharing of drinks and cups can be achieved by referring to the form of shared bikes.

References

1. Li, X.: A brief discussion on the changes of Taiwan's milk tea culture in the past thirty years. Commun. Res. **4**(14), 14–15 (2020)
2. Vezzoli, C., Ceschin, F., Diehl, J.: Sustainable Product-Service System Design applied to Distributed Renewable Energy fostering the goal of sustainable energy for all. J. Clean. Prod. **97**, 134–136 (2015). https://doi.org/10.1016/j.jclepro.2015.02.069
3. Yuan, L., Fabrizio, C., Noha, M., David, H.: Product–service systems applied to reusable packaging systems: a strategic design tool. Des. Manag. J. **15**(1), 15–32 (2021)
4. Bitner, M., Ostrom, A., Morgan, F.: Service Blueprinting: A Practical Technique for Service Innovation. Calif. Manag. Rev. **50**(3), 66–94 (2008). https://doi.org/10.2307/41166446
5. Kano, N., et al.: Attractive quality and must-be quality. J. Jpn. Soc. Qual. Control **4**(2), 147–156 (1984)
6. Hou, Z., Chen, S.: Research on adjustment method of user requirement importance based on Kano model. Comput. Integr. Manuf. Syst. **11**(12), 1785–1789 (2005)
7. Meng, Q.: Customer Value Driven Customer Relationship Management and Its Effectiveness Evaluation, pp. 130–134. China Materials Publishing House, Beijing (2011)
8. Munasinghe, M.: Sustainomics and sustainable development. http://editors.eol.org/eoearth/wiki/Sustainomics_and_sustainable_development (2007)
9. Manzini, E., Vezzoli, C.: A strategic design approach to develop sustainable product service systems: examples taken from the 'environmentally friendly innovation' Italian prize. J. Clean. Prod. **11**(8), 851–857 (2003). https://doi.org/10.1016/S0959-6526(02)00153-1

Research and Enterprise for Sustainable Hemp Products and Buildings

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Abstract. This paper presents a research work aimed at promoting eco-sustainability and biocompatibility in the construction sector through a collaboration between the University and local entrepreneurs, according to the guidelines of the European Community. The study concerns the use of hemp sativa for the manufacturing of products and building elements and the use of these in the redevelopment of existing buildings or in the construction of new buildings with low environmental weight. Having recognized the potential of hemp (especially as regards the provision of wellness, environmental protection and safety benefits) in the creation of an architecture that is friendly to man and the environment, the study focuses on the advantages of raw material use in building interventions (considering the environmental criticality characterizing the contemporary landscape) and the environmental limits to be overcome with specific assessments for the same products. For the use of hemp in construction, the relationships between the material, the life of the buildings, the architectural quality, the images of the landscapes and the possible repercussions in terms of sustainable development. That is the way for defining beauty-oriented solutions through the dialogue between buildings and ecosystems, for the quality of human life. The critical points of the life cycle phases of the examined hemp-based products are also highlighted, to guide effective evaluation processes, according to regenerative approaches inspired by nature. The work, referring to the context of the Abruzzo region (Italy), aims to provide a tangible contribution to the triggering of circular economies and building practices characterized by a strong balance between man, architecture and nature.

Keywords: Human-friendly buildings and products · Beauty · Hemp architecture · Life cycle assessment

1 Introduction

The contemporary scenario demands a drastic reduction of the building sector ecological footprint which should hopefully lead to benefits in the economic and social spheres. In building design and production for sustainability scope, this condition results, first of all, in the need of "putting into operation the creativity" of scholars and researchers to improve the achieved results about materials, construction systems and low-impact buildings. The awareness that the construction sector research fields should define a correct dialogue between the building practice and the ecosystems, adopting regenerative

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approaches inspired by natural cycles, is the main stimulus that motivates this work. Although the bio-ecological architecture sector has been active for several years, in Italy there are still no sufficiently consolidated and widespread practices that define closed cycles for the creation of products and buildings that are convenient for humans and the environment. This paper presents a research in progress that wants to establish a close relationship between raw materials, products, construction elements and buildings. So by making the availability of raw materials an important design aspect and by working for disseminating and transferring eco-compatible products from a niche dimension to all construction activity, we want to trigger sustainable development processes.

Fig. 1. The coexistence of marine, hilly and mountain environments in the Abruzzo landscape

The raw material on which the work is focused is hemp sativa and the fields of investigation concern the production of technical elements (blocks, panels, mortars and plasters) and classes of technical elements (semi-finished walls) as well as their use in the redevelopment or in the construction of buildings conceived according to ecosystem logic. The context is the Abruzzo region (Italy), characterized by the coexistence of different natural environments (marine, hilly, mountain), by consistent green and cultivable areas (see Fig. 1) and by the need of "repairing" and protecting the images of landscapes.

These characteristics influenced the choice of hemp since good possibilities for the production of the raw material were recognized. The products that hemp plants provide represent an interesting field of investigation because, starting from the rediscovery of an ancient tradition crop, effective answers and inputs can be provided to solve current problems.

2 Beautiful Buildings for People and Ecosystems

2.1 Towards the Transition of the Construction Sector

The objectives of this work support the most recent European indications, such as those of the "Renovation Wave" with which, the European Commission reiterated the need of making our buildings green, creating jobs and improving people's lives through major changes in building practice. Indeed, the construction sector will be able to find a way out of the crisis only by changing its aims, to intercept people's and planet survival needs. This means focusing mainly on maximizing the possibilities of using all the available buildings instead of designing new buildings and transforming new lands, for reducing the raw materials and energy consumption. Our objectives also recall the intentions of the "European Green Deal" which foresees, among other things, the promotion of a resources efficient use, the transition to a clean and circular economy and the restoration of biodiversity. This shares the concept of beauty that the "New European Bauhaus" brings back to solutions capable of establishing a dialogue between the built environment and natural ecosystems.

Today, studies and solutions often address in a limited, partial and separate way the problems related to biocompatibility, interventions on the existing buildings, the incorporated impacts of the products, the need for timeliness and cost-effectiveness and safety. Most building products have a low level of environmental compatibility, if we consider all stages of the life cycle. Semi-finished products and components are often produced with not local raw materials, strongly affecting the transport phases and aggravating the environmental balance even of materials with a good eco-profile [3].

In current practice, the construction systems provide lasting buildings, realized with non-reversible processes and components with scarce possibilities of recycling and reuse. Then the study of hemp building products is oriented towards the search for beautiful, sustainable and inclusive architecture. The study is developed through a collaboration between the Italian University[1] and the local enterprise sector[2] for the Life Cycle Assessment of hemp products, their use in the design of semi-finished construction elements for existing or new buildings.

Further developments involve the conclusion of the LCA [2] and the improving of some aspects through a collaboration with the German University.[3] From these collaborations, the project of an industrial doctoral scholarship[4] was presented and financed, with the National Operational Program for Research and Innovation 2014–2020.

The work outlines perspectives for a local development through an industrial research and an integrated approach between planning for sustainability and Life Cycle Thinking (LCT). The research theme is coherent with the National Strategy of Intelligent Specialization (SNSI) and involves three thematic areas (1. "Smart and sustainable industry, energy and environment", for the relaunch of green building through sustainable products innovation; 2. "Health, nutrition, quality of life", for new solutions experimentation based on a "healthy" connection between food, energy, material and architecture; 3. "Tourism, cultural heritage and creativity industry, for national resources enhancement through a "sustainable" redevelopment of the built environment). So we think of a building way

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[2] In particular with Edilcanapa srl of Mosciano Sant'angelo (Teramo, Abruzzo, Italy).

[3] RWTH_Rheinisch-Westfälische Technische Hochschule, Aachen University, Germany.

[4] XXXV cycle of the Ph.D. Terrestrial systems and built environments of the DdA - Architecture and InGeo-Engineering and Geology of the G. D'Annunzio University of Chieti-Pescara, Abruzzo, Italy, Health, Environment and Architecture scholarship. Materials and components for product innovation in Sustainable Design, PhD student Maria Chiara Capasso, tutor Donatella Radogna, co-tutor Luciana Mastrolonardo.

that, through a link between agriculture, business and architecture, suggests strategies to trigger new circular economies, reduce pollution and combat climate changes.

2.2 The Research Iter to Promote Building with Hemp

The research aims at improving the sustainability of products and building elements, identifying the limits characterizing the current situation and trying to provide tools to overcome them.

An important reference are the CEN/TC 350 "Sustainability on constructions works" standards which propose a methodology for evaluating buildings environmental, social and economic performance [1].

The research is divided into the following phases: 1. Meta-project analysis for isolating problems, structuring knowledge and organizing information, identifying constraints and opportunities for product innovation and local development; 2. Strategic analysis and product Brief for describing the expected results and identifying the environmental and social impact indicators and technological requirements, for the development and evaluation of the innovation process produced in the green building sector; 3. Concept development for displaying original concepts of components and subsystems that best meet the strategic research objectives; 4. Verifications of manufacturing and building possibilities, to define the product parts dimensions and characteristics to be implemented according to reversible processes,; 5. Prototyping and physical simulations of product components and subsystems, for further evaluations and comparisons with the evaluations results, and possible re-design of parts and components.

Having sanctioned the greater sustainability of the existing building redevelopment compared to new buildings, the use of the proposed products can define important intervention principles for a buildings controlled transformation in favor of climate neutrality (see Fig. 2, which shows the use of hemp walls in the redevelopment of an abandoned multi-storey car park). Products such as blocks, hemp and lime-based plasters significantly improve the energy performance of buildings and define reversible solutions for future reuse or recycling operations. The proposed products are particularly appropriate for carrying out projects aimed at protecting the characteristics of traditional buildings and images, natural landscapes as well as the improvement of buildings without architectural quality [6]. With this in mind, the objectives for buildings safeguard extend to the protection of the well-being of the planet and people, overcoming the limits dictated by the separate conception of the areas of production, design and construction.

In the Abruzzo Region there are three different natural environments (coast, hill and mountain), in which there are fairly recent construction (reinforced concrete and perforated brick), traditional architectures (with wooden roofs and brick or clay or stone walls) and fallow fields. The abandoned buildings offer excellent supports for the application of the products studied, to favor an ecological transition and promote a circular architecture able to be easily reused. Strategic hypotheses for the reuse of buildings can determine the spread of forms of slow tourism for the development of marginal areas [7]. Uncultivated fields could be used for hemp sativa as well as for other crops capable of regenerating economic, natural and social systems, creating a dialogue between the built environment and ecosystems. To achieve the expected results, however, it is necessary to overcome a series of limitations including the lack of information which translates into

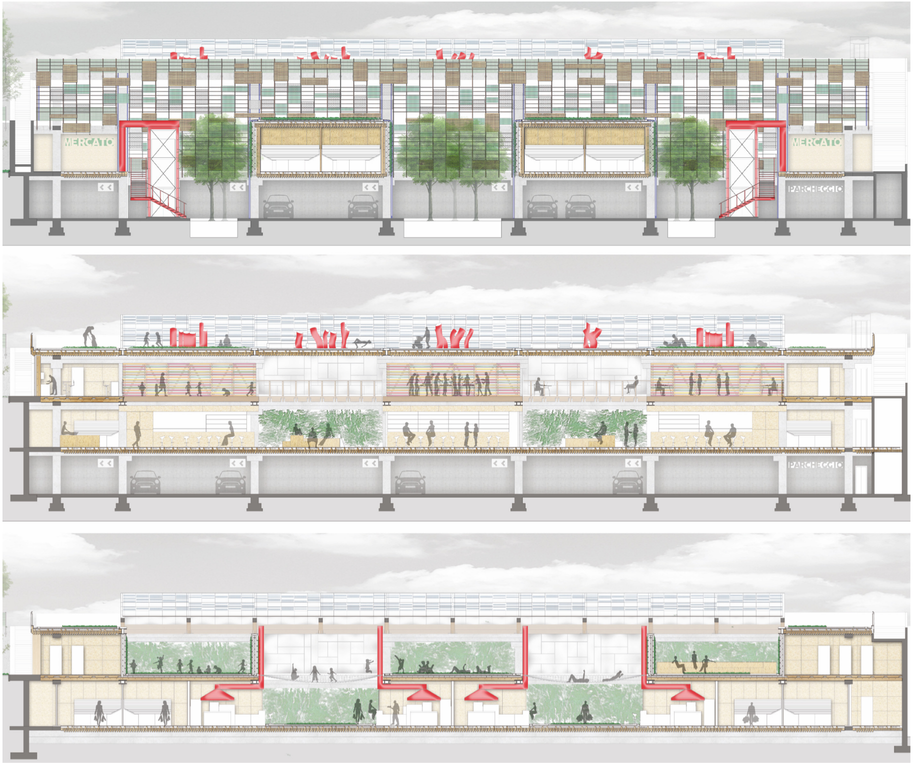

Fig. 2. Agriculture and architecture for the redevelopment of the abandoned multi-storey car park in San Salvo (Chieti, Italy)

mistrust in innovations, the scarce availability of data necessary for the development of the studies and the need to update the regulatory instruments [4]. Important progress can be made, however, if these limits become new works and a source of income, as well as the achievement of sustainability.

3 Limits and Prospective of Life Cycle Assessment for Hemp Products

3.1 Low Impact of Hemp Products in Building Sector

At the building level, significant contribution to reduce pollution is given by due to consumption of both embodied energy and natural resources as well as to emissions to air, water and soil during all the phases of their life-cycles, including the end of life. The embodied energy is expressed as primary energy and represents the energy sequestered in buildings, in technical solutions and in building materials during all processes of production, on-site construction, and both demolition and disposal. Direct and indirect energy are the two primary components of the embodied energy: direct energy is used for construction, renovation, and demolition of a building; indirect energy is consumed by a building for production of the materials used in its construction and installations. In addition to the embodied energy, the operational energy should also be considered when intending to assess building life-cycle.

If the more sustainable building is the one not build, the cheapest energy is always the one that is unused. In some cases this statement might be questioned, for example, when an extra of insulation is added on an already well insulated building enveloped and sometimes, could happen that the benefit in terms of energy conservation is no longer justfied based upon the energy used for production, installation, use and disposal of the insulation system used. The importance of environmental evaluation is increasing with the systemic efficiency of building. In comparative evaluations, therefore, it is necessary to be able to benefit from data and evaluations useful to have a clear picture of each type of energy used in the building. The study and methods for understand all impact on the environmental, economic and social system is Life Cycle Assessment (LCA), for systemic estimation of the energy efficiency and of the environmental and economic sustainability related to buildings. Low carbon and low embodied energy building materials in buildings are the right choice, thus highlighting the difficulties found in measuring and comparing embodied energy, the develop of LCA studies contribute to efforts to develop new materials with less embodied energy, like hemp.

Despite in recent years, there have been numerous studies aimed at supporting the sustainability of materials of petrochemical origin, starting from life cycle analyses, and from the potential recyclability within the techno cycles, the use of natural materials represents one of the best pathways to achieve energy efficiency and environmental sustainability in buildings. In particular, this research was focused upon industrial hemp because its sustainability is not determined just by the natural origin e the renewability but also by all the life cycle phases (from cradle to cradle) of the building process [6], furthermore is acknowledged world-wide as one of the most used and potential vegetal materials in buildings, though in Italy its market has to explode yet.

In the light of their environmental soundness, the hemp-based materials are commonly used in the green building sector where selection of construction materials is based upon recyclability and renewability of raw materials, and low consumption of resources in the involved production processes. The use of this natural materials allows for environmental benefit such as reduction of resource consumption; low levels of embodied energy, reduced GHG-emissions; and recovery, re-use, and recycling of the products before the final disposal. Additionally, hemp based materials can be considered as eco-friendly, since they cause no release in the environment of toxic substances that affect human health and the environment.

This aspect is mainly attributable to the growing interest and attention towards the field of production and application of hemp-based materials in the last decades by the involved stakeholders, such as designers, researchers, builders and company owners. These stakeholders are increasingly becoming aware of the environmental benefits resulting from using these materials in buildings and they request assessments of the related structural, mechanical, but also on life cycle cost and environmental aspects in order to enable further improvement and innovation of these materials as well as of the construction technologies involved.

3.2 Use of Hemp in the Building: Material Properties

Hemp stem consists of a woody core surrounded by an outer skin containing long and strong fibres. Hemp fibres are the most valuable part of the plant, and in the building industry they are usually used as insulation, hemp hurds are instead extensively used in hemp lime products. The hemp has, in the growing phase, a lot of advantages: the un use of pesticides, very low water consumption, it adapts to several microclimates (grown throughout Italy), is fast in growth (3–4 months), it has a high yield in terms of plant mass (it also reaches 5–6 m in height), cleans and re-mineralizes the soil, preparing it to other crops. The biological analysis of hemp show that the hemp (or hemp wood) obtained from the stem of the dried plant, having a hive-like molecular structure, is breathable, has a high thermal power, is at the same time ductile and durable, thanks to the content of cellulose in the fibre.

These characteristics of the hemp fibre allow the products to be:

– excellent thermal and acoustic insulators
– breathable and therefore dehumidifying and anti-mold
– antiseptics and anti-rodents
– ideal for construction in seismic areas.

Hemp wood therefore represents the inert body of the conglomerate to which, like binder, NHL5 hydraulic lime was combined which, with its specific characteristics, combined with those of the hemp shives, generates a material capable of blending perfectly. These environmental aspects had already been highlighted by van der Werf [8]. who conducted LCA to compare the environmental impacts of cultivation of hemp to those of the cultivation of other annual crops, such as sunflower, pea, wheat and maize. This study showed that hemp is one of the less harmful crops with highly reduced impacts when it comes to eutrophication, climate change and energy use, hence recommended for building applications. Hemp-fibre mats are valid alternatives to conventional materials and are feasible for application in the green-building sector.

3.3 LCA on Local Hemp Products Construction Industry

Developing a comprehensive LCA analysis of local hemp products would help the industry to develop and to overcome barriers of various kinds. Indeed, some technical barriers to the use of hemp concern problems related to the breeding and processing of the local hemp market which, above all in Italy, is recovering but very fragmented, as well as the lack of some technological supply chains and its use by the construction sector. The regulatory apparatus does not help the development of hemp cultivation and only some regions of northern Italy have succeeded, with specific economic actions to make it take off. In Abruzzo we need a lobby that starts with stakeholders active at different levels and identifies the potential for sustainability in an irreproachable way, precisely through an in-depth study of sustainability through the LCA methodology.

The diffusion of a “hemp architecture” in Italy has an important through the use of materials for processing transformation and laboratory testing and LCA analysis, aimed at certifying the quality of semi-finished products and products (especially in terms of

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Fig. 3. Life stages and modules for the building assessment in UNI EN 15804, core rules for the product category of construction products.

safety, well-being and environmental protection). The most important aspect to investigate regards eco-profile of hemp product, the raw material supply chain, manufacturing (product stage), and also the end of life scenarios (Fig. 3).

In LCA upstream process as already mentioned, the increased cultivation of the hemp brings so many benefits to the soil and can heal the soil, either by integrating it, giving it the chance to "reproduce," which cleanses it from heavy metals, as well as subtracting from the atmosphere of CO2 through the photosynthesis process. The raw material is from the northern part of Italy, with a lot of positive environmental earnings. For the core process the local enterprise Edilcanapa produces a lot of technical solution hemp-lime based:

1. Natural mortar and thermal plaster: the first a biocomposite material formed by the mixture of the woody core of the hemp plant (hemp wood), and a lime based binder with the addition of water, the second is a mix must contain a greater amount of lime, this system is used as well as for buildings built entirely with the biocomposite and particularly suitable if applied on traditional walls and is effective in the thermal upgrade of old stone constructions.
2. Thermal and acoustic insulation: the company has a patent for insulation sheets thermal and acoustic self-supporting and rigid, usable as insulation (self-supporting rigid panels), as well as insulating panels with variable density (from 60 to 100 kg/mc) usable both as external insulation and as a cavity.
3. Brick: hemp brick are formed by certifies hemp wood, and a lime based binder. It is a mixture of hemp, lime and water without additional additives (Fig. 4).

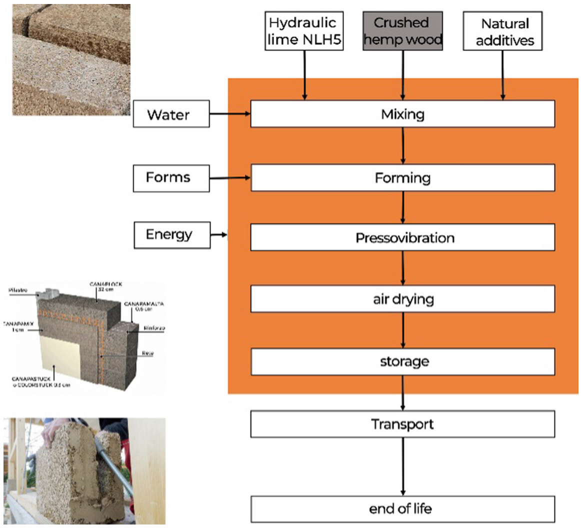

Fig. 4. Life cycle of hemp brick made in Edilcanapa.

Lime-hemp combines the vapour permeability of lime and the hygroscopicity of hemp, with the capacity to absorb high quantities of vapour water. Walls and floors of a lime-hemp building can breathe thus absorbing moisture and successively releasing it through evaporation. This feature avoids the build-up of dampness and associate deterioration within the materials, as well as reducing the moisture content inside the building.

For the downstream process the lime and hemp biocomposite can once arrived at end of life, can be reused, chopped and added a small amount of lime and water, allowing me to reject or produce new hemp and lime blocks. If the hemp and lime biocomposite is released into the environment, the lime crumbles and in-creases the pH of the soil, but hemp is no longer protected, biodegrades naturally.

3.4 Perspectives for Life Cycle Assessment of Italian Hemp Products

Despite of the energy and environmental soundness of hemp-based materials, there exist principally-economic weaknesses which can result in negative prospects for local industrial hemp. In particular, hemp fiber have a two to four times higher cost price compared to conventional materials such as glass and mineral wool. Italian and EU-policy could restore healthy competition between these crops, thus giving industrial hemp the possibility to overcome barriers faced during its infancy phase.

For this reason the development of a series of LCAs on local hemp products, that we are studying with primary company data, takes on particular urgency, in general for the hemp market for several issues:

Economic: the development of a hemp architecture, especially for some types of products, is currently experiencing a favorable moment of development, induced not only by the green products market, but by the new bonuses induced by the post-covid relaunch decree (dl 34/2020), which offers the possibility of renovating the most energy-intensive homes at almost zero cost. This national strategy for the relaunch of the construction sector and for the relaunch of the green economy, has in fact flattened the costs of some materials, through a doping effect on the market that has caused the prices of building raw materials to rise, in particular with respect to materials. For thermal insulation (part of the legal interventions, therefore mandatory), which have always been the most used, opening up a previously unthinkable slice of the market.

Environmental: the company has managed, after several years, to change its suppliers in favor of an Italian market. The objective in the coming years is to encourage an ever greater regionalization of the product, through production and above all local quality processing (by activating a 100% local supply chain). Activating an LCA and recognition through EPD labeling would help the product to be recognizable on the market, which made CAM (Italian GPP strategy) mandatory in the funded interventions.

Competitive: in spite of its young age, Edilcanapa is characterized as Italian excellence in the production of hemp materials, having developed a series of patents that give it a competitive advantage over other companies, to be exploited in the short term, not to lose it, and only a environmental recognition of products can push in this direction.

Social: the working methods of the company's plants are on a human scale and have a particular ethics and attention, in addition to individual stakeholders, also to investments in research of part of the profit. In addition they invest in industrial research, in quality certification, and in technical people formation.

4 Conclusions

The study foresees new research paths for what concerns the structural capabilities of hemp fibers and the possibility of designing products (based on hemp and waste) that can be used with 3D printers.

The achievement of the expected results could also be an example to stimulate new studies on building practices with low environmental weight and advantageous for society, based on a correspondence between agriculture, industry and architecture and between renewable resources and planet regeneration.

A raw material such as hemp could also stimulate studies on the use of new products, composed for example of secondary raw materials. In this logic, the key words are reuse and recycling of products as well as buildings. The hemp-based elements, considered in this study, provide for simple and fast deconstruction operations and are totally reusable or recyclable.

The collaboration between different sectors (Agriculture, Architecture) and different areas (Research, Enterprise) reveal how the most important resilience capacities, arise from what has been mainly damaged that is to say nature and people.

In this vision, the built environment can be one of the most effective means that can help man to get up and to reconcile with the planet. Today, in fact, the construction sector, despite the damages it caused in the past, is one of the resources through which ecology can help raise the economic conditions of communities [5].

Architecture can have a new "social role" if the interests of nature and men will coincide with those of the construction sector (if buildings will be made of natural materials whose production can determine positive effects such planet regeneration economic benefits for people, food, etc.), according to a win win philosophy.

References

1. Andreotti, J., Faruku, D., Giordano, R.: Cross-Fertilization Between Architecture and Agricultural: A Circular Supply Chain. In: Littlewood, J., Howlett, R.J., Jain, L.C. (eds.) Sustainability in Energy and Buildings 2020. SIST, vol. 203, pp. 243–254. Springer, Singapore (2021). https://doi.org/10.1007/978-981-15-8783-2_20
2. Capasso, M.C.: Hemp-block wall design and life-cycle assessment. In: Howlett, R., Jain, L.C. (eds.) Smart Innovation, Systems and Technologies/Sustainable Design and Manufacturing 2021, Springer, Heidelberg (2021)
3. Mastrolonardo, L.: Progettazione ambientale a chilometro zero. Sostenibilità ed ecologia industriale per lo sviluppo di filiere edili. Maggioli, Rimini (2016)
4. Monticelli, C.: Life cycle design in architettura. Progetto e valutazione di impatto ambientale dalla materia all'edificio. Maggioli, Rimini (2013)
5. Pauli, G.: Blue Economy 2.0. Edizioni Ambiente, Milano (2015)
6. Radogna, D., Mastrolonardo, L., Forlani, M.C.: (2018): Hemp for a healthy and sustainable building in Abruzzo. In: Karwowski, W., Ahram, T. (eds.) Intelligent Human Systems Integration. Advances in Intelligent Systems and Computing 2018, vol. 722, pp. 720–726. Springer, Heidelberg (2018)
7. Radogna, D., Viskovic, A.: Environmental design, building reclamation and slow tourism for a sustainable development. Vitruvio **3**(2), 54–64 (2018)
8. Van der Werf, H.M.G., Turunen, L.: The environmental impacts of the production of hemp and flax textile yarn. Ind. Crops Prod. **27**, 1–10 (2008)

Environmental and Economic Assessment of the PET Bottles Manufacturing Process: A Case Study

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Abstract. By using an integrated methodology, the purpose of this paper is to present the environmental and economic evaluation of the extended production process of polyethylene terephthalate (PET) bottles for soft drinks in the context of the Greek economy. Such an evaluation can lead to improvements, which are highly desirable since the large quantities of plastic bottles produced every year worldwide, contributing to a significant environmental footprint. We use the Environmental Performance of Industrial Processes (EPIP) method that enables the identification of the production process stages, which have critical environmental impact and the highest contribution to the overall environmental costs, thus facilitating the application of targeted interventions. After identifying the production stages with severe environmental impacts in a real industrial environment, using the same method, we assess the impact of targeted interventions.

Keywords: PET production process · Sustainability assessment · Improvement

1 Introduction

Climate change results in even hotter days, some of which are unbearable in areas with hot and humid climate. People drink water and soft drinks in both work and leisure activities to avoid dehydration and feel better. As a result, the consumption of such refreshments follows an ever increasing trend, further intensified by other socio-economic factors. It is estimated that the soft drinks market in the USA will reach in 2028 the 320 billion dollars mark, from 253 billion in 2016 [1]. Similar trends are observed for the European market [2]. In Greece, which is the focus of this study, despite the economic crisis, the soft drinks market increased by an average of 6% annually to reach 650 million Euros in 2019 [3]. A comparable trend was observed in the bottled water market, where consumption reached 95 lt/head annually, from 30 lt/head ten years before. The average figure in other European countries is 150 lt/head, annually. Mirasgedis et al. [4] estimated an increase of 1,2% in the sales of soft drinks, 1,1% in bottled mineral water, 2,9% in carbonated water, and 3,1 in juices in the period 2021–2050 *solely* due to climate. As the majority of these products are available in PET bottles, it follows that their production and use follows similar increasing trends with the corresponding environmental burdens.

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In general, industrial activities, such as PET production, consume large amounts of natural resources and generate large quantities of waste in solid, liquid and gaseous forms. Clearly, such activities impact human health negatively, while important costs at the micro, as well as macro-economic levels, are incurred when attempts to mitigate impacts are undertaken. This makes the simultaneous environmental and economic evaluation of industrial processes a very important task as it may help in balancing the trade-offs between economic development and environmental sustainability. Consequently, the choice of an assessment method must not be based solely on its measurement potential, but also in its ability to provide leads for mitigating environmental impacts at acceptable costs. There are a large number of methods for the evaluation of the environmental performance and the sustainability of industrial systems (e.g. [5–8]). While such methods offer substantial information on the performance of a process, they lack attention on industrial systems as wholes, which include "back-office" support activities [7]. The "Environmental Performance of Industrial Processes" (EPIP) [9] method used in this paper overcomes this drawback allowing the evaluation of extended production processes by identifying the activities with the worst environmental performance.

EPIP uses two groups of variables – environmental and economic – based on the Life Cycle Impact Assessment [10] and IMPACT 2002+ [11] methods. Despite the importance of such an endeavor, most of the research efforts so far were directed towards the after-use environmental assessment of PET bottles (e.g. [12–14]). Not much research effort has been directed towards the PET-bottles production process *per se* and its environmental impacts with methods providing leads for improvements [15].

The research presented in the paper is based on real data from a production process of a Greek soft drinks producer operating for a period of one calendar year (2019). In that year, the specific company produced 82,150,000 preforms corresponding to 82,000,000 PET bottles. Taking into account the weight of each bottle, the primary PET used was 1.812 tons. Following in the paper, we first briefly present the EPIP method, and then we apply it for the assessment of the specific process in two rounds (before and after targeted improvements were accomplished).

2 The Environmental Performance of Industrial Processes (EPIP) Method

Based on a study of widely used assessment methods and tools, which included Material Flow Cost Accounting (MFCA) [6, 8], Life Cycle Impact Assessment (LCIA) [16–18] and Environmental Risk Analysis (ERA) [19], eight evaluation categories were selected by the developers of EPIP, which are used for the specific case of PET bottles: 1) Material Balance; 2) Energy Balance; 3) Destinations of solid, liquid and gaseous emissions; 4) Environmental Impact Assessment; 5) Environmental costs incurred related to materials, energy and emissions; 6) Degree of legal compliance and compliance to stakeholder requirements, which is contingent to particular geographic context; 7) Surrounding environment conditions; and 8) Applied measures to prevent pollution [9].

The core of the EPIP method is an equation that calculates the equivalent cost *CEA(n)* of each environmental aspect *n* summing the values of *Material Loss Cost* (*MLC(n)*), *Consumed Energy Cost* (*CEC(n)*), *Material Destination Cost* (*MDC(n)*) and *Environmental Management Cost* (*EMC(n)*), constitute the *Economic Analysis Group*, and the values of *Impacts of Consumption* and *Emission Materials* (*IM(n)*) and *Impacts of Energy Consumption* (*IE(n)*), which constitute the *Environmental Analysis Group*. The sum of the former variables is denoted by *EcG(n)*, whereas those of the latter by *EnG(n)*. *CEA(n)* is measured in $\$_{Eq}$ (Equivalent Currency Units).

The application process of the EPIP comprises six steps: *Mapping processes, boundary, functional units and environmental aspects*; *Specification of mass, energy and operation costs in the process*; *Determination of management costs*; *Data collection for Life Cycle Impact Assessment (LCIA)*; *LCIA weights assignment*; *Calculations and analysis of results*. Details are depicted in the specific application below.

After the application, decision-makers are able to identify the most critical environmental aspects and to take improve actions. Then, after the implementation of the improvements, the method is applied again to evaluate the improvements of the environmental aspects covered by the actions, and to identify new critical environmental aspects for improvement, maintaining a continuous improvement cycle towards environmental sustainability.

3 Sustainability Assessment of PET Bottle Production: A Case Study

3.1 The Assessment Process

EPIP was used for evaluating the environmental and economic performance of the PET bottle production process in a specific company in Greece. The process was installed in the facilities of a brand soft drinks producer, and operates exclusively for its needs. The process produces PET bottles of various sizes (330 mL, 500 mL and 1500 mL) and colors (blue, green and transparent). In 2019, a total of 82,118,912 bottles of various sizes and colors were produced, of which 81,995,918 were actually used (99.9% yield). The corresponding volumes of preforms used were 82,143,548, 82,118,904, and 24,643, respectively. The total quantity of raw material (PET granulated) used was 1,812,301 kg.

The production process consists of two stages. During the first stage, the preforms are made (by injection molding – thermoforming), whereas in the second the bottles are produced (by stretch blow molding – thermoforming). The application of the EPIP methodology, stage by stage, and the information obtained was as follows:

I. *Mapping processes, boundary, functional unit and environmental aspect*

Initially, the homogenization of PET granules takes place. Then, PET melts at an average temperature of 285–290 °C (extrusion process). While the PET remains hot and homogenized, it is colored by a dosing pump, and is stirred until a complete uniform coloring is reached. The injection machine is fed with this fluid (colored) PET mixture. This machine uses suitable molds to produce the preforms. The preforms are cooled by cool air having a temperature of about 5 °C, collected and finally stored in specially designed containers. Then in a second phase, the blowing machine is fed with the preforms produced, which are then heated around their external surface by using hot air of an average temperature of 85–90 °C. Following, using compressed air, the preforms inflate into molds to get their final shape. The bottles are then cooled by cold air at a temperature of 10 °C.

II. *Specification of mass, energy and operation costs in the process*

The information for mass, energy and operation costs for each environmental aspect was obtained from orders of supplies, from the technical manual of equipment of the industry and interviews with process operators (Table 1).

III. *Determination of management costs*

Considering that it was the initial implementation of EPIP in this process, no data on environmental management costs were available. There were available afterwards.

IV. *Data collection for Life Cycle Impact Assessment (LCIA)*

The impact categories concerning each environmental aspect were identified, after the quantification of the data which were needed for the economic analysis. Using the information already collected on materials, emissions, water and energy for each environmental aspect, each impact category was evaluated.

V. *LCIA weights assignment*

The weighting factors used in the Analytic Hierarchy Process method [25] for the damage categories are shown in Table 2.

VI. *Calculations and analysis of results*

Table 1 depicts indicatively the calculations for the economic analysis group of EPIP, for the production steps with the highest overall environmental impacts (see Sect. 3.2). The values listed correspond to a period of one calendar month. For the environmental analysis group, the impact categories considered by *IM(n)* are shown in Table 3. The table shows Impact Categories and the corresponding Damage Categories based on [11] and [20]. Normalization Factors and their units are based on the same literature. Midpoint Characterization Factors $(CF^m)\, IC_j(n)$ [$kg_{eq\ (category)}$/kg], were compiled based on [20–24]. The Weighting Factors came from the application of AHP [25].

3.2 Analysis of Results

Employing the computational logic of EPIP, the equivalent costs for each environmental aspect were first obtained (Tables 1 and 3), and then, the results from the total equivalent cost of the industrial process were assessed. The total equivalent cost was 1,146,791.44 $R\$_{Eq}$ per production month. The six environmental aspects with the highest *overall equivalent costs* (worst Environmental Performance) shown in Table 1 and Fig. 1 are: 1) Volatile Organic Compounds (VOC) of dry offset coloring (A25), 2) PET bottles thermoforming (A09), 3) PET preforms thermoforming (A08), 4) Steam (A06), 5) Cotton waste with color of coloring (A21) and 6) Blanket consumption (A23), which corresponds to 99,1% of the total equivalent relative cost.

The results of the *economic analysis group* indicated that the aspects having the highest costs were: 1) PET bottles thermoforming (A09), 2) PET performs thermoforming (A08), 3) Generated pallets (A01), 4) Blanket consumption (A23), 5) Cotton waste with color of coloring (A21) and 6) VOC's of dry offset coloring (A25), which corresponds to 84,8% of the total economic group analysis relative cost (Table 1). PET bottles thermoforming (A09) and PET preforms thermoforming (A08) exhibit high costs because they consume much energy.

The results of the *environmental analysis group* show that the environmental aspects that had the highest impacts were: 1) VOC's of dry offset coloring (A25), 2) Steam (A06), 3) PET bottles thermoforming (A09), 4) PET preforms thermoforming (A08) and 5) Cleaning product packaging (A28), which corresponds to 84% of the sum of variables of the environmental analysis group (total impact of environmental aspects). This was expected as VOC's of dry offset coloring (A25) has the highest contribution due to photochemical oxidation. PET bottles thermoforming (A09), PET performs thermoforming (A08) and Cleaning product packaging (A28) belong also to the highest impact categories, due to the generation of bulk waste in large quantities and the use of much energy (Table 1).

The waste destination streams that were considered to calculate *MDC(n)* were (in parenthesis the corresponding code): reuse at source (1), reuse inside the industrial process (2), recycle inside the industrial process (3), reuse in other industrial process (4), recycle in other industrial process (5), waste treatment inside the industrial process with internal disposal (6), waste treatment inside the industrial process with external disposal (7), transport, treatment, and external disposal (8), transport and external disposal without treatment (9), and unsuitable disposal (which does not comply with legal requirements) (10).

When comparing the rankings of the environmental aspects between the economic analysis group, the environmental analysis group and the aggregated/overall performance, it is possible to observe differences in the improvement priorities. The ranking of the environmental aspects provided by EPIP indicate, as priority environmental aspects, those with the highest costs, which are directly related to the inefficiency of material and energy transformation, and/or those with the highest environmental impacts, which are related to the quantity and severity of the level of impact.

Clearly, the six high impact/cost environmental aspects are related to activities, such as, coloring of bottles by VOCs emission, thermoforming of PET preforms/bottles due to the high energy consumption of the machinery, extrusion by evaporation of the cooling water, coloring of PET performs by large volume of waste and blanket consumption. Based on the initial assessment, the managers of this process triggered improvement initiatives regarding these aspects, and after their definition and implementation, a new application of the EPIP tool evaluated the change in the environmental performance of the process, with a view to environmental sustainability.

Table 1. Economic analysis group variables for the processes/aspects with the worst environmental performance

Economic analysis group (case study)														
			MLC (n)			CEC (n)				MDC (n)				EcG (n)
Id (n)	Process	Environmental aspect	Output (kg)	Material Cost (R$/kg)	R$	CE (kWh)	EUC(R$/kWh)	PE (%)	R$	Destination type (d)	Percentage destination (%)	Destination Cost (R$/kg)	R$	R$
A01	Receipt and storage	Generated pallets	4396.00	1.32	**5802.72**	0.00	0.0964	0.00000	**0.00**	4	1	−0,38	**−1670,48**	4.132,24
A06	PET Extrusion	Steam	123000.00	0.00632	**777.36**	23450.00	0.0964	0.07500	**169.54**	10	1	0,00	**0,00**	946,90
A08	Thermoforming	PET preforms	0.00	0.00	**0.00**	118000.00	0.0964	0.99970	**11371.79**	0	0	0,00	**0,00**	11.371,79
A09	Thermoforming	PET bottles	0.00	0.00	**0.00**	121200.00	0.0964	0.99850	**11666.15**	0	0	0,00	**0,00**	11.666,15
A21	Dry offset coloring	Cotton waste with color	225.00	6.10	**1372.50**	0.00	0.0964	0.00000	**0.00**	10	1	1,85	**416,25**	1.788,75
A23	Dry offset coloring	Blanket consumption	93.00	30.50	**2836.50**	0.00	0.0964	0.00000	**0.00**	9	1	1,85	**172,05**	3.008,55
A25	Dry offset coloring	VOCs of coloring	177.88	8.60	**1529.81**	2814.94	0.0964	0.05500	**14.92**	10	1	0,00	**0,00**	1.544,73
A28	Cleaning	Cleaning product packaging	7.68	0.00	**0.00**	0.00	0.0964	0.00000	**0.00**	9	1	0,65	**4,99**	4,99

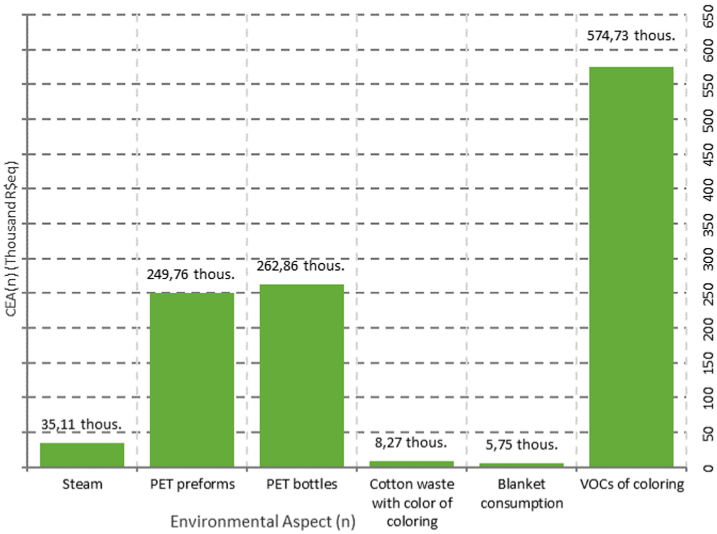

Fig. 1. Results obtained for the six aspects with the worst environmental performance.

Table 2. Damage categories by the AHP method and weighting factors

Damage categories	Weighting factor (W_j)
Human health	61.3
Resources	28.3
Ecosystem quality	7.4
Climate change	3.0

3.3 Improvement Initiatives and Their Effects

As it was already indicated, the main problem in this process were the emissions of chloroethylene and PM2.5 in the coloring of bottles and the high cost of energy consumption mainly during the processes PET preforms/PET bottles thermoforming.

After was decided to reduce the amount of color in the bottles by half, EPIP was used again to find out the impact of this intervention in the process. The total equivalent cost in the second implementation of EPIP was 717,226.81 R$\$_{Eq}$ per month of PET bottles production. The six worst-performing environmental aspects (Table 4 and Fig. 2) are the same as those in the initial use of EPIP.

Hence, we can conclude that after the improvements, the equivalent total cost (*TC*) decreased by 37.46% compared to that of the initial assessment. This result proves the importance of the decision support that the method provides in the improvement of the environmental performance of industrial processes.

Table 3. Impact categories considered in the environmental analysis group by EPIP.

Environmental analysis group (case study)						
Impact category (j)	Damage categories	Normalization factor	Unit N_j	Term calculation	Weighting factor	Term calculation
j	Hembert (V2.2.1)	N_j		$IC_j(n)$ [$kg_{Eq(category)}$/kg]	W_j	[$W_j \times IC_j(n)$]/N_j
Human toxicity	Human health	219	kg chloroethylene into aireq/pers/y	0.0015	61.3	4.199E−04
Respiratory effects	Human health	8.8	kg PM2,5 into aireq/pers/y	0.3	61.3	2.090E+00
Ionizing radiation	Human health	533000	Bq Carbon-14 into aireq/pers/y	0.14	61.3	1.610E−05
Ozone layer depletion	Human health	0.204	kg CFC-11 into aireq/pers/y	0.04	7.4	1.451E+00
Photochemical oxidation	Human health	12.4	kg ethylene into aireq/pers/y	1	61.3	4.944E+00
Global warming	Climate change	11600	kg CO_2 into aireq/pers/y	1	3	2.586E−04
Aquatic ecotoxicity	Ecosystem quality	1360000	kg triethylene glycol into watereq/pers/y	0.013	7.4	7.074E−08
Terrestrial ecotoxicity	Ecosystem quality	1200000	kg triethylene glycol into soileq/pers/y	0.11	7.4	6.783E−07
Aquatic acidification	Ecosystem quality	66.2	kg SO_2 into aireq/pers/y	1	7.4	1.118E−01
Aquatic eutrophication	Ecosystem quality	14.3	kg PO_4^{3-} into watereq/pers/y	1	7.4	5.175E−01

(*continued*)

Table 3. (*continued*)

Environmental analysis group (case study)						
Impact category (j)	Damage categories	Normalization factor	Unit N_j	Term calculation	Weighting factor	Term calculation
j	Hembert (V2.2.1)	N_j		$IC_j(n)$ [$kg_{Eq(category)}/kg$]	W_j	$[W_j \times IC_j(n)]/N_j$
Terrestrial acidification/nitrification	Ecosystem quality	315	kg SO_2 into aireq/pers/y	1	7.4	2.349E−02
Bulk waste	Ecosystem quality	1726	kg bulk wasteeq/pers/y	0.018	7.4	7.717E−05
Hazardous waste	Ecosystem quality	180	kg hazardous wasteeq/pers/y	0.5	7.4	2.056E−02
Water scarcity index (WSI)	Ecosystem quality	365000	kg water withdrawaleq/pers/y	0.245	7.4	4.967E−06
Non-renewable energy	Resources	152000	MJ/pers/y	8.58	28.3	1.597E−03
Renewable energy	Resources	152000	MJ/pers/y	1	28.3	1.862E−04
Mineral extraction	Resources	5730	kg iron (in ore)eq/pers/y	1	28.3	4.939E−03

Table 4. Aspects with the worst environmental performance after improvements

Id (n)	Process	Environmental Aspect	EcG (n) (R$)	EnG(n)	CEA(n) (R$)
A06	PET Extrusion	Steam	946.90	37.08	35,114.50
A08	Thermoforming	PET preforms	11371.79	21.96	249,760.23
A09	Thermoforming	PET bottles	11666.15	22.53	262,858.04
A21	Dry offset coloring	Cotton waste with color of coloring	1788.75	4.63	8,272.97
A23	Dry offset coloring	Blanket consumption	3008.55	1.91	5,751.34
A25	Dry offset coloring	VOCs of coloring	779.83	186.15	145,167.94

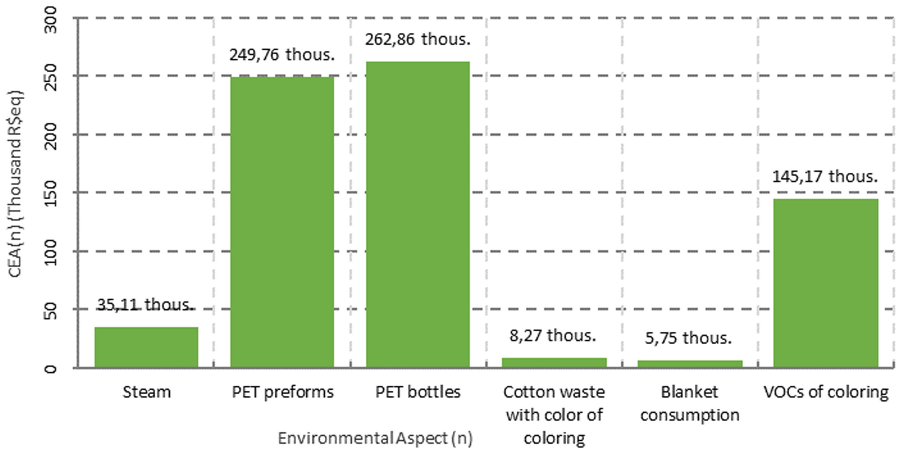

Fig. 2. Results obtained for the six environmental aspects with the worst environmental performance after improvements were implemented

4 Conclusions

The purpose of this paper was twofold: First, to perform a complete environmental and economic evaluation of the production process of PET bottles for soft drinks, in order to identify the environmental aspects and the production stages that have the highest environmental impact. Second, to demonstrate the application of an integrated assessment method (EPIP) for the environmental assessment and improvement of a production process. Regarding, the former, the results have showed that the environmental aspects with the worst environmental performance in PET bottle production were: steam, PET preforms (thermoforming), PET bottles (thermoforming), cotton waste with color of coloring, blanket consumption and VOCs of coloring which corresponds to 99.1% of the total equivalent relative cost. Regarding the latter, the application case presented, demonstrated the ability of the EPIP method to identify aspects and stages with the worse environmental performance in a different process (initial application was in yoghurt cups manufacturing) and to suggest targeted interventions. Overall, the method provides an easy to use decision support tool that can contribute to the sustainability of many industrial processes that have high social and economic impact, especially in societies and economies that are reliant on a clean environment as the Greek one is, due to the share of tourism in it GDP.

References

1. Grand View Research: U.S. Soft Drinks Market Size, Share & Trends Analysis Report By Product (Carbonated Drinks, Packaged Water, Iced/RTD Tea Drinks, Fruit Beverages, Energy Drinks) And Segment Forecasts, 2018–2025, San Francisco, CA (2018)
2. FoodDrink Europe: Data & Trends: EU Food and Drink Industry. Brussels (2016)
3. ICAP: 40 High Performance Sectors in Greece, Athens Chamber of Industry and Commerce, Athens (2016)
4. Mirasgedis, S., Georgopoulou, E., Sarafidis, Y., Papagiannaki, K., Lalas, D.P.: The impact of climate change on the pattern of demand for bottled water and non-alcoholic beverages. Bus. Strateg. Environ. **23**, 272–288 (2014)
5. Poveda, C.A., Lipsett, M.G.: A review of sustainability assessment and sustainability/environmental rating systems and credit weighting tools. J. Sustain. Dev. **4**(6), 36–55 (2011)
6. Schmidt, M., Nakajima, M.: Material flow cost accounting as an approach to improve resource efficiency in manufacturing companies. Resources **2**, 358–369 (2013)
7. Angelakoglou, K., Gaidajis, G.: A review of methods contributing to the assessment of the environmental sustainability of industrial systems. J. Clean. Prod. **108**, 725–747 (2015)
8. Chompu-Inwai, R., Jaimjit, B., Premsuriyanunt, P.: A combination of material flow cost accounting and design of experiments techniques in an SME: the case of a wood products manufacturing company in Northern Thailand. J. Clean. Prod. **108**, 1352–1364 (2015)
9. Maceno, M.M.C., Pawlowsky, U., Machado, K.S., Seleme, R.: Environmental performance evaluation – a proposed analytical tool for an industrial process application. J. Clean. Prod. **172**, 1452–1464 (2018)
10. ISO: ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization ISO (2006)
11. Jolliet, O., et al.: IMPACT 2002+: a new life cycle impact assessment methodology. Int. J. Life Cycle Asses. **8**, 324–330 (2003)
12. Choudhary, K., Sangwan, K.S., Goyal, D.: Environment and economic impacts assessment of PET waste recycling with conventional and renewable sources of energy. Procedia CIRP **80**, 422–427 (2019)
13. Gomes, T.S., Visconte, L.L.Y., Pacheco, E.B.A.V.: Life cycle assessment of polyethylene terephthalate packaging: an overview. J. Polym. Environ. **27**(3), 533–548 (2019)
14. Balazińska, M., Kruczek, M., Bondaruk, J.: The environmental impact of various forms of waste PET bottle management. Int. J. Sustain. Dev. World Ecol. **28**(5), 473–480 (2020)
15. Ayalon, O., Avnimelech, Y., Shechter, M.: Application of comparative multidimensional life cycle analysis in solid waste management policy: the case study of soft drink containers. Environ. Sci. Policy **3**, 135–144 (2000)
16. Elduque, A., Elduque, D., Javierre, C., Fernandez, A., Santolaria, J.: Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts. J. Clean. Prod. **108**, 80–89 (2015)
17. Hermann, B.G., Kroeze, C., Jawjit, W.: Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. J. Clean. Prod. **15**, 1787–1796 (2007)

18. Jawjit, W., Pavasant, P., Kroeze, C.: Evaluating environmental performance of concentrated latex production in Thailand. J. Clean. Prod. **98**, 84–91 (2015)
19. Wrisberg, N., Helias, A., de Haes, Udo, Triebswetter, U., Eder, P., Clift, R. (eds.): Analytical Tools for Environmental Design and Management in a Systems Perspective. Springer Netherlands, Dordrecht (2002)
20. Humbert, S., De Schryver, A., Bengoa, X., Margni, M., Jolliet, O.: IMPACT 2002+: User Guide. Draft for Version Q2.21 (Version Adapted for Quantis) (2014)
21. Danish Environmental Protection Agency, 2005: Spatial differentiation in life cycle impact assessment – The EDIP 2003 Methodology (2005)
22. Althaus, H.-J., et al.: Implementation of life cycle impact assessment methods. In: Frischknecht, R., Jungbluth, N. (eds). Swiss Centre for Life Cycle Inventories, ecoinvent report No. 3, v2.0, Dübendorf (2007)
23. Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm R.: ReCiPe 2008: a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First ed. Report I: Characterisation (2009)
24. Humbert, S., De Schryver, A., Margni, M., Jolliet, O.: IMPACT 2002+: User Guide. Draft for Version Q2.2 (Version Adapted by Quantis) (2012)
25. Saaty, T.L.: The Analytical Hierarchy Process: Planning, Priority Setting Resource Allocation. McGrawHill, New York (1980)

Green Supply Chain Management in Greece: Practices and Attitudes in Environmental Assessment and Selection of Suppliers

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Abstract. The paper presents a survey of the practices and attitudes of Greek Purchasing Managers towards green sourcing. By adopting a macro-level practice perspective, a questionnaire recording such practices and attitudes at the strategic level was developed and distributed to purchasing managers. A total of 749 responses indicated an overall support for green sourcing. However, although purchasing managers consider important the audits of their suppliers, they trust more third parties for carrying out such as assessments. In addition, it seems they prefer to have suppliers at a distance in strategic issues related to green supply chain management. And although they support a stricter environmental legislation in general, they are not so enthusiastic when this legislation concerns their supply chain management practices. These somehow contradicting results provide leads for focusing in-depth qualitative research to understand Purchasing Managers behavior with respect to green sourcing.

Keywords: Green supply chain management · Green purchasing · Supplier · Environmental assessment · Practices · Attitudes · Greece

1 Introduction

As the pressure towards environmentally benign operations extends beyond the widely-assumed boundaries of firms to include their suppliers and customers activities [1, 2], in an era where the consequences of climate change are more obvious [3, 4], Green Supply Chain Management (GSCM) has attracted much interest in both academia and industry. GSCM has emerged as a strategy that takes into account green design and new product development, green manufacturing, green packaging, green purchasing, as well as other activities related to social issues, such as the health and safety of employees and customers [5, 6]. In the GSCM context, it has been suggested that in order to achieve the objective of sustainability, companies must pay closer attention to the *upstream* part of the supply chain [7]. Following such calls, green purchasing/sourcing has attracted increasing interest [8], as it is an upstream activity that, in addition, consumes a great portion of a firm's capital resources [2]. Apart from this, the importance of the purchasing

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function has increased, following a trend in outsourcing, with firms focusing on their core activities and sourcing components and services needed for them [9]. In addition, green purchasing absorbs pressures from a range of stakeholders that include government and international regulators, who want to promote a greener business environment [10, 11].

There are many definitions of green purchasing in the context of green supply chain management. For instance, Gavronski et al. [12] define GSCM as "the complex of mechanisms implemented at the corporate and plant level to assess or improve the environmental performance of a supplier base". Large and Thomsen [13] define environmental or green purchasing as an integration of environmental considerations into purchasing policies, programs and actions. In more specific terms, Carter et al. [14] maintained that environmental purchasing implies the involvement of the purchasing function/department in Life Cycle Analysis and environmental design for recycling, reuse and resource reduction. In a different perspective, Zsidisin and Siferd [15] defined environmental purchasing as all the activities related to the acquisition of raw materials, suppliers operations, inbound distribution, production, packaging, etc., until the final disposal of the firm's products. Govindan [5] integrated and simplified all the above in arguing that the general term "green purchasing" is "nothing but purchasing with green concern".

Overall, there are mixed results as far as the contribution of green purchasing to environmental performance is concerned [16]. This may be the result of sparse research exclusively on the supply side of green supply chain management [2, 17], as well as its unclear relationship to specific performance objectives [2]. In addition to the relationship between green supply implementation and performance, research has focused on environmental characteristics of products and services sourced [5], on attributes of suppliers that play a significant role in selection and partnerships, human purchasing resources development for green sourcing [4], as well as on practices of green purchasing in specific sectors and geographic areas [6, 11, 18]. In parallel, a lot of research has been pursued on developing mathematical methods for green supplier evaluation and selection based on multi-criteria optimization and other operational research (OR) methods [19].

The current paper introduces a different research perspective to green sourcing. It aims at recording environmental-management-related practices at-large in the evaluation and selection of suppliers carried out by purchasing departments, as well as the latter's attitudes towards important organizational and behavioral attributes of their suppliers in a specific socio-economic and legislative context. Recording practices and attitudes provides a more realistic picture of green sourcing as the implementation and performance of formal processes and contracts (why and how they are employed) is highly influenced by them. The research was carried by sampling 749 purchasing managers in an equal number of companies of various sectors operating in Greece. Greece is a case example of a country in which green purchasing is of particular importance. It is consumption-driven economy, significantly dependent on imports of materials, components and devices, while, at the same time, most of its GDP (around 25%) [20] is related to tourism and related services that require a benign natural environment.

2 Practices of Supplier Evaluation and Attitudes on Green Supply

So far, the strategic consideration of environmental purchasing has been confined to top-down planning approaches [21] or lately to the resource-based view of strategy [4, 12, 22]. In line with the practice turn in the general strategy literature that considers strategy as an essentially emergent phenomenon arising from specific individuals' attitudes and interests (the emphasis is on what strategists do, rather than on what strategies companies have) [23], in this paper, we focus on the attitudes and practices *at-large* (wide and long-term) of Purchasing Managers, which influence the micro-level every-day practices of green purchasing strategic activities. Clearly, such practices are influenced by the national socio-economic context in which they are embedded. Hence, understanding this context and the attitudes of purchasing managers towards this is of great interest.

In the current dynamic fast-changing environment, consistency in the characteristics and behaviors of suppliers is of great importance for buyers. As things change fast and competition becomes multi-dimensional (cost, speed, flexibility, etc.), it is possible that suppliers give higher priority to different operations strategic objectives, such as cost, at the expense of sustainability [24]. Regular environmental assessment of the suppliers guarantees strategic consistency with respect to environmental performance for both partners involved in the supply relationship [6], and detects possible opportunistic behaviors of suppliers which divert from long-term agreements [25]. This implies that the Purchasing Department should maintain its monitoring capability at a high level by considering the environmental assessment process as critical in its operation [26]. Greater interest in green supply is reified by performing audits in the suppliers' premises. Of course, this is an involving process requiring commitment by both parties involved, and definitely assumes a high degree of integration of the processes of the focal company with its suppliers [17, 27]. In a different perspective, it denotes a lack of trust, which, in the long run, may damage the producer-supplier relationship and its strategic significance as an organizational resource (social capital) [5, 28]. The lack of trust would be evident through the engagement of certified third parties for carrying out the environmental assessment of suppliers [5, 29]. The employment of specialized organizations to carry out environmental assessment of suppliers may attributed to lack of knowledge or ability on the part of the Purchasing Department [6], or a matter of confidence to carry out this task, or even a trend of mimicking/following common industry practices [30]. In general, involving a certified agency makes the assessment more formal and transparent to interested third parties, such as governmental organizations, which frequently require certain levels of environmental performance from the suppliers of their suppliers.

Independent of who performs the assessment, its outcome may be crucial for the selection (or not) of a supplier, i.e. the assessment may directly lead to selection. Similarly, the environmental evaluation of a supplier may have a different impact on its overall evaluation as supplier, as other characteristics may be considered more important [6, 31]. However, the environmental assessment of a supplier is definitely important when its environmental performance is directly linked to the overall performance of the buyer's supply chain [31], and to the cost of the supply chain more specifically [2, 32].

Moving from practices of environmental assessment to attitudes towards specific sustainability-related attributes of suppliers, clearly, the ecological footprint of a supplier will be considered as a critical factor for its selection [21, 33]. For many companies, of the same importance are generic behaviors related to honesty and transparency. In the context of the environmental assessment of suppliers, the former is directly related to "greenwashing" behavior, and the latter to the transparency and objectivity of the suppliers' assessment methods and their outcomes [6]. Usually, in addition to the establishment of an appropriate sustainability-inspired organizational culture and consciousness [10], the commitment of a supplier organization to sustainability is demonstrated by the establishment of a dedicated organizational unit [2], as well as by its participation in industry-wide environmental initiatives implemented through specialized task forces and/or working groups, workshops, training programs, etc. [6]. As far as the relation of suppliers to the producer is concerned, it is important that the former are in step with the environmental initiatives of the latter, both in content and in pace [2, 21].

At the boundary between the attitudes towards suppliers' environmental attributes and the general (national) socio-economic and legislative environment rests the degree of trust a purchasing department has in the certification of a supplier [18, 29]. The legislative framework may be considered sufficient, or just as a basis for more improvements. The same is true for more globally acceptable frameworks and standards, such as the ISO 14000 set of environmental management standards [25].

3 Research Methods

Based on the above considerations, the aim of the research presented in the paper was to inquiry how these global green supply concerns were taken into consideration by Purchasing Managers in a peripheral European economy (Greece). As, in the initial stage, the specific objective of the research was of exploratory nature, quantitative survey and descriptive statistics were selected as research method.

A questionnaire comprising of twenty (20) questions was developed (Table 1) to record attitudes and practices of Greek Purchasing Managers as determinants of, or, at least influencing, their company's strategies towards green sourcing. Questions were grouped according to the three areas of inquiry identified in the previous section. More specifically: The first group of questions (#1–9) inquired about the practices (expected ways of action) of companies for the process of evaluation and selection of their (current or potential) suppliers, including the frequency, the significance, the conductor of the process, etc. A second group of questions (#10–17) aimed at exploring the attitudes (settled ways of thinking) towards specific environmental characteristics and behaviors of their suppliers, such as "greenwashing" behavior, suppliers who follow consistently company's environmental initiatives, have an environmental certification, demonstrate an environmental culture, etc. Finally, a small number of questions (#18–20) asked the opinion (trust and acceptance) of Purchase Managers regarding the existing regulatory framework, including the Greek environmental legislation and the existing environmental certification schemes. The questionnaire was tested and validated by a group of two academics and three professional Purchasing Managers.

All answers were recorded on a 5-Point Likert Scale from "Strongly Disagree" to "Strongly Agree." The questionnaire was sent electronically to almost 10,000 Greek companies and the corresponding link was active for a period of four months (from 1st of March 2020 to the 30th of June 2020). To increase the geographical and sectoral variability of the data, the lists of participating companies were collected from twelve (12) Business Chambers of Greece, which cover several prefectures of the country, and a wide spectrum of sectors (manufacturing, craft, process industry, recycling, food & beverages, housing, construction, import – export, and general commerce).

4 Results

A total of 749 valid responses were received (the response rate was slightly over 7%). 27.3% of the responders belonged to the light industry and crafts sector (incl. food and beverages), 10.9% to the heavy industry (incl. renewable energy devices and equipment), 18% to services (incl. tourism and related services), and 43.2% belonged to commerce/trade sector. The participation of sectors in the sample is roughly similar to the distribution of sectors in the Greek economy. Responses (percentages of agreement/disagreement with questions/statements of the questionnaire items) are tabulated in Table 1. The data reliability statistical analysis resulted in a Cronbach Alpha of 0.889. The suffix “g” in the item number (first column) indicates that the item is taken into account in determining the overall “greenness” of Purchasing Departments (see below).

The results depicted in the table can be summarized as follows:

Regarding the practices for the evaluation and the selection of the suppliers, the survey reveals that:

- four in five Greek companies (their Purchasing Managers) prefer the environmental evaluation of their suppliers to take place on a regular basis, and to be part of their suppliers’ overall evaluation.
- roughly the same percentage (≈80%) of managers considers the auditing of the environmental commitments of their suppliers important, and indicates that environmental auditing should be conducted by specialized agencies.
- three in five Purchasing Managers do not want their department/unit to carry out the environmental audit of their suppliers.
- more than two in five managers appear neutral to the fact that environmental evaluation of their suppliers improves the total supply chain costs, while a 34% of the respondents are positive, and a percentage of 24% is negative.

As for the attitudes on suppliers’ environmental characteristics, the responses show:

- a high percentage (67%) of companies is determined to reject an existing supplier in a case of ‘greenwashing’ behavior.
- in the same vein, one may find high percentages in favor of a supplier with an environmental culture and consciousness (86%), a low ecological footprint (62%), or transparent environmental assessment/management processes.
- An interesting point is that a moderate percentage (44%) appears positive to the fact that their suppliers should follow consistently the environmental improvement initiatives of their clients, while 47% of the firms appear neutral to the same option. Surprisingly, one in five companies appears negative to this possibility.

Table 1. Results of the survey (749 answers). [SA: Strongly Agree; A: Agree; AD: neither Agree nor Disagree; D: Disagree; SD: Strongly Disagree]

#	Question	Answers (%)				
		SA	A	AD	D	SD
1g	The environmental evaluation of suppliers should take place on a regular basis	29,6	52,5	14,6	2,9	0,4
2	The environmental evaluation of suppliers is important for (the operation) of our Procurement Dpt.	21,1	52,9	19,9	4,8	1,3
3_g	Auditing of suppliers' environmental commitment(s) is important	26,6	56,5	13,0	2,9	1,1
4	Environmental audits of suppliers should be conducted by specialized agencies	30,8	51,0	13,1	4,3	0,8
5	Environmental audits of suppliers should be conducted by the Procurement Dpt.	3,2	12,2	26,7	47,8	10,2
6_g	The environmental evaluation of a supplier is critical for its selection	11,6	44,9	32,6	9,0	2,0
7	The environmental evaluation of our suppliers improves our supply chain	12,0	55,3	24,3	6,7	1,7
8	The environmental evaluation of our suppliers improves the total supply chain costs	6,3	27,5	42,6	19,1	4,5
9_g	The environmental behavior of a supplier should be part of a supplier's overall evaluation	30,3	55,0	10,7	2,3	1,7
10_g	'Greenwashing' suppliers should be rejected	23,6	43,4	25,2	6,7	1,1
11	A supplier should maintain a specialized environmental management department	11,2	42,5	33,1	10,0	3,2
12_g	A supplier should employ transparent environmental assessment/management processes	12,0	50,2	28,4	7,7	1,6
13_g	A supplier should participate in industry-specific environmental initiatives	10,2	43,7	36,3	7,9	2,0
14_g	A supplier should follow consistently our environmental improvement initiatives	10,0	34,5	36,9	15,8	2,9
15_g	The ecological footprint of a supplier's product/service is a critical factor for its selection	11,2	50,6	26,7	9,2	2,3
16_g	A supplier should demonstrate an environmental culture and consciousness	25,1	60,8	11,0	1,7	1,5
17_g	A supplier with an environmental certification should be trusted	15,1	50,2	27,9	5,2	1,6
18_g	Existing environmental certification schemes are crucial for green sourcing	3,1	17,5	41,9	33,4	4,1
19	Greek environmental legislation is sufficient for green procurement	1,5	14,4	46,3	31,4	6,4

(*continued*)

Table 1. (*continued*)

#	Question	Answers (%)				
		SA	A	AD	D	SD
20_g	Greek environmental legislation should become more strict	35,4	49,3	11,2	3,2	0,9

The answers of the participating managers to questions related to the existing regulatory framework indicate that:

– a high percentage (85%) of Greek companies is in support of a more strict environmental legislation
– a significant part of participants, when asked about both the significance of existing environmental certification schemes for green supply chain, and the sufficiency of the national environmental legislation for green procurement, appears either neutral (≈44%) or negative (38%).

5 Analysis and Short Discussion

Table 2 below summarizes the stronger (individual item) consensus, namely the highest percentages in positive (agree + strongly agree), neutral (neither agree + nor agree) or negative (disagree + strongly disagree) responses. Given that the majority of questions has a green perspective, in the sense that they seek to find out the importance given to an environment-friendly characteristic or behavior, the fact that the top-five percentages indicating a positive stance (82–86%) are by far higher compared to those assuming a neutral one (36–46%), and even more higher compared to the negative one (13–58%) indicates an overall positive attitude towards green sourcing. In the same vein, Table 1 shows that in the majority of questions, a negative perspective exists in less than 10%.

This apparent overall support for green sourcing is further justified by combining 14 items of the questionnaire (marked with a "g" suffix in Table 1) in a compound "greenness of sourcing" index for the sample that averages the percentages of agreement for each scale element, for all the items included. Questions whose answers are not indicative for a clear environmental-friendly stance, such as "*The environmental audit of a supplier should be conducted by our Procurement Department*" were not included. Figure 1 shows the distribution of the average values of the percentages of support for each of the items of the index. An overall positive stance towards green sourcing of the companies that participated in the survey is clearly indicated.

Looking closer at the responses from a critical perspective, one can note that, on the one hand, there is an apparent reluctance on the part of Purchasing Managers to undertake the task of auditing suppliers for environmental compliance (item #5) and a propensity to outsource this activity, while on the other, they value high the environmental assessment of suppliers for their selection (item #6). This indicates a reluctance to take responsibility and to be directly involved with suppliers, at least, as far as environmental activities are concerned. A preference for an arms-length relationship with suppliers is also evident in the limited support for the possibility of involving suppliers in environmental initiatives (item #14). Finally, it is worth noting the low importance given to the contribution of green sourcing on the overall supply chain costs (item #8) and the limited support for existing environmental schemes, probably because they are being considered as not strict enough. Clearly, these somehow contradicting results, attributed to organizational issues, necessitate the employment of qualitative methods for their investigation and eventual explanation.

Table 2. Practices and attitudes towards green supply chain: the tops in each stance

Rank	Positive responses (agree)	Neutral responses	Negative responses (disagree)
1	A supplier should demonstrate environmental culture (86%)	Greek environmental legislation is sufficient for green procurement (46%)	Environmental audits of suppliers should be conducted by the Procurement Dpt. (58%)
2	The environmental behaviour of a supplier should be part of a supplier's overall evaluation (85%)	The environmental evaluation of our suppliers improves the total supply chain costs (43%)	Existing environmental certification schemes are crucial for green supply (38%)
3	Greek environmental legislation should become more strict (85%)	Existing environmental certification schemes are crucial for green supply (42%)	Greek environmental legislation is sufficient for green procurement (38%)
4	Auditing of suppliers' environmental commitment(s) is important (83%)	A supplier should follow consistently our environmental improvement initiatives (37%)	A supplier should follow consistently our environmental improvement initiatives (19%)
5	Environmental audits of suppliers should be conducted by specialized agencies (82%)	A supplier should participate in industry-specific environmental initiatives (36%)	A supplier should maintain a specialized environmental management department (13%)

6 Concluding Remarks

In this paper, we investigated the practices and attitudes of Greek Purchasing Managers regarding environmental sourcing from a strategic practice perspective. This is one of the rare studies focusing exclusively on the green procurement activity adopting the strategy-as-practice perspective at this level. The results of the study are based on 749 Greek firms and are in the form of descriptive statistics. Although they reveal an overall support for green sourcing practices, some individual answers are worth noting: Purchasing Managers seem reluctant to engage with their suppliers in strategic environmental supply chain management activities/initiatives that may reduce the costs of their organization's supply chain demanding a stricter environmental legislation for outsourcing environmental auditing activities. Such contradicting results necessitate a more in-depth investigation based on qualitative methodologies (to observe practices *in-situ*). The research presented in this paper provides the stepping stone in in this direction.

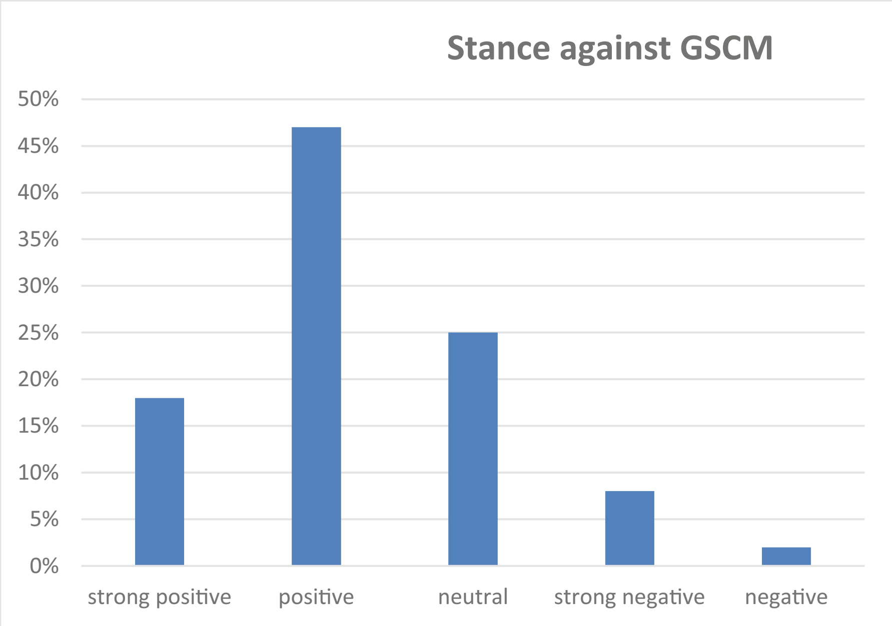

Fig. 1. ‘Greenness’ of sourcing practices and attitudes of Greek firms.

References

1. Papachristos, G., Adamides, E.D.: Internal supply-chain competition in remanufacturing: operations strategies, performance and environmental effects. Int. J. Logist. Syst. Manag. **19**(2), 187–211 (2014)
2. Ghosh, M.: Determinants of green procurement implementation and its impact on firm performance. J. Manuf. Technol. Manag. **30**(2), 462–482 (2019)
3. Mirhedayatian, S.M., Azadi, M., Farzipoor, S.R.: A novel data envelopment analysis model for evaluating green supply chain management. Int. J. Prod. Econ. **174**, 544–554 (2014)
4. Yu, W., Chavez, R., Feng, M.: Green supply management and performance: a resource-based view. Prod. Plann. Control **28**(6–8), 659–670 (2017)
5. Govindan, K.: Green sourcing: taking steps to achieve sustainability management and conservation of resources. Resour. Conserv. Recycl. **104**, 320–333 (2015)
6. Mosgaard, M.A.: Improving the practices of green procurement of minor items. J. Clean. Prod. **90**, 264–274 (2015)
7. Kähkönen, A.-K., Lintukangas, L., Hallikas, J.: Sustainable supply chain management practices: making a difference in a firm’s sustainability performance. Supply Chain Manag. Int. J. **23**(6), 618–530 (2018)
8. Guinipero, L.C., Bittner, S., Shanks, I., Cho, M.H.: Analyzing the sourcing literature: over two decades of research. J. Purch. Supply Chain Manag. **25**, 100521 (2019)
9. Lee, V.H., Ooi, K.B., Ching, A.Y.L., Lin, B.: A structural analysis of greening the supplier, environmental performance and competitive advantage. Prod. Plann. Control **26**(2), 116–130 (2015)
10. Michelsen, O., de Boer, L.: Green procurement in Norway: a survey of practices at the municipal level. J. Environ. Manag. **91**, 160–167 (2009)

11. Ciumara, T., Lupu, I.: Green procurement practices in Romania: evidence from a survey at the level of local authorities. Sustainability **12**, 1–13 (2020)
12. Gavronski, I., Klassen, R.D., Vachon, S., Nascimento, L.F.M.: A resource-based view of green supply management. Transp. Res. Part E Logist. Transp. Rev. **47**(6), 872–885 (2011)
13. Large, R.O., Thomsen, C.G.: Drivers of green supply management performance: evidence from Germany. J. Purchas. Supply Chain Manag. **17**(3), 176–184 (2011)
14. Carter, C.R., Ellram, L.M., Ready, K.J.: Environmental purchasing: benchmarking our German counterparts. Int. J. Purchas. Mater. Manag. **34**(3), 28–38 (1998)
15. Zsidisin, G.A., Siferd, S.P.: Environmental purchasing: a framework for theory development. Eur. J. Purchas. Supply Chain Manag. **7**(1), 61–73 (2001)
16. Jabbour, A.B.L.S., Frascareli, F.C.O., Jabbour, C.J.C.: Green supply chain management and firms' performance: understanding potential relationships and the role of green sourcing and some other green practices. Resour. Conserv. Recycl. **104**, 366–374 (2015)
17. Blome, C., Hollos, D., Paulraj, A.: GP and green supplier development: antecedents and effects on supplier performance. Int. J. Prod. Res. **52**(1), 32–49 (2014)
18. Min, H., Choi, S.-B.: Green sourcing practices in Korea. Manag. Res. Rev. **43**(1), 1–18 (2020)
19. Zhang, Q., Pan, J., Jiang, Y., Feng, T.: The impact of green supplier integration on firm performance: the mediating role of social capital accumulation. J. Purchas. Supply Chain Manag. **26**, 100579 (2020)
20. OECD: OECD Economic Surveys: Greece 2020 (2020)
21. Sroufe, R.: A framework for strategic environmental sourcing. In: Sarkis, J. (ed.) Greening the Supply Chain, pp. 3–23. Springer, London (2006). https://doi.org/10.1007/1-84628-299-3_1
22. Arora, A., Arora, A.S., Sivakumar, K., Burke, G.: Strategic sustainable purchasing, environmental collaboration, and organizational sustainability performance: the moderating role of supply chain base size. Supply Chain Manag. Int. J. **25**(6), 709–728 (2020)
23. Jarzabkowski, P.: Strategy as Practice: An Activity Based Approach. Sage, London (2005)
24. Sancha, C., Wong, C.W.Y., Gimenez, C.: Do dependent suppliers benefit from firms' sustainability practices? J. Purchas. Supply Chain Manag. **25**, 100542 (2019)
25. Leppelt, T., Foerstl, K., Reuter, C., Hartmann, E.: Sustainability management beyond organizational boundaries – sustainable supplier relationship management in the chemical industry. J. Clean. Prod. **56**(1), 94–102 (2013)
26. Lee, S.-Y.: The effects of green supply chain management on the supplier's performance through social capital accumulation. Supply Chain Manag. Int. J. **20**(1), 42–55 (2015)
27. Vachon, S., Klassen, R.D.: Environmental management and manufacturing performance: the role of collaboration in the supply chain. Int. J. Prod. Econ. **111**(2), 299–315 (2008)
28. Sarkis, J., Zhu, Q., Lai, K.H.: An organizational theoretic review of green supply chain management literature. Int. J. Prod. Econ. **130**(1), 1–15 (2011)
29. Chen, C.C.: Incorporating green purchasing into the frame of ISO14000. J. Clean. Prod. **13**, 927–933 (2005)
30. Renwick, D.W.S., Redman, T., Maguire, S.: Green human resource management: a review and research agenda. Int. J. Manag. Rev. **15**, 1–14 (2013)
31. Appolloni, A., Sun, H., Jia, F., Li, X.: Green procurement in the private sector: a state of the art review between 1996 and 2013. J. Clean. Prod. **85**, 122–133 (2014)
32. Large, R.O., Kramer, N., Hartmann, R.K.: Procurement and logistics services and sustainable development in Europe: fields of activity and empirical results. J. Purchas. Supply Chain Manag. **19**(3), 122–133 (2013)
33. Zhang, L.-J., Liu, R., Liu, H.-C., Shi, H.: Green supplier evaluation and selection: a state-of-the-art literature review of models, methods, and applications. Math. Probl. Eng. **2020** (2020). Article ID: 1783421

Fabrication, and Experimental Evaluation of Shape Memory Alloy Based Spring Actuators for Laparoscopic Grippers

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Abstract. This work contributes to a novel method of manufacturing a Shape Memory Alloy (SMA) based spring actuators for Laparoscopic grippers. The actuator was manufactured using a novel fixturing method followed by a heat treatment process. Afterwards, the developed actuator samples were tested using Differential Scanning Calorimetry (DSC) for transformation temperature investigation and Energy-dispersive X-ray Spectroscopy (EDX) was performed to account for the elemental composition of the utilized SMA material. The characterized spring actuator element is coupled to a gripper manufactured by a combination of conventional manufacturing and rapid prototyping techniques. A testing apparatus was introduced which was used to evaluate the operation of the gripper. Finally, the sustainability in SMA based actuation technologies was highlighted using inherent properties of the SMA materials.

Keywords: Shape Memory Alloy · Differential Scanning Calorimetry · Energy-dispersive X-ray spectroscopy · Spring actuator · Rapid prototyping · Laparoscopic gripper · Sustainable manufacturing

1 Introduction

Shape Memory Alloys (SMAs) belong to a special material category which can memorize an artificially trained shape under external stimulations. The stimulations can either be thermal or magnetic. Considering thermal stimulation of the material, heating beyond a specific temperature would cause a solid state phase transformation. This phenomenon significantly changes the shape of the material [1] from a deformed shape to a parent shape.

Prior going in to more details, it is important to identify the SMA manufacturing techniques and study how those techniques affect phase transformation temperatures.

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SMA ingots are formed using several processing techniques including Vacuum Induction Melting, Plasma Melting, Vacuum Arc Melting, Electron Beam Melting and, Powder Metallurgy [2]. For a selected process, Ni – pellets and Ti – bars/disks are being melted inside crucibles. Here, the crucible material is also important as the final composition and the transformation characteristics are mainly depending on inclusion of third material to the matrix. These formed ingots in the cast state are characterized by a very low formability and usually only a small or no memory or super elastic effect.

Mostly the raw SMA materials are available in the form of wires, sheets, tubes, plates. These forms are manufactured using hot or cold forming techniques. Wires are manufactured by subjecting cast ingots to forging (hot/cold) followed by swaging (hot/cold) and finally subjecting to drawing (hot/cold) operation. Sheets are formed by forging (hot/cold) or rolling (hot/cold) operations. Strips are made by rolling. Also bars are manufactured by forging followed by swaging operation [2].

Transformation behavior of a SMA is affected by the above mentioned operations. After hot forming of alloys, heat treatment is generally applied. The effect of annealing temperature and cooling rate is presented in many occasions and it is evident that in order to achieve controllable transformation temperatures, there should be annealing process followed prior to use of standard forms [2]. Because the transformation temperatures are unpredictable during material processing. Also, there is a significant influence in cold working on the SMA properties. So, it is better to form the material in required shapes according to the applications and follow with annealing [3].

Influencing factors for the different transformation temperatures are the composition of the material (i.e.: Percentage of Ni, Ti and other minor elements) [4], presence of precipitations, annealing temperature and time and finally the cooling mode. SMA materials inherently possess two types of crystal structures namely, Austenite and Martensite. Transformation between these phases occur due to external stress applied to the material and the temperature. There are four characteristic temperature values related to the SMAs known as Martensite start and finish temperature and Austenite start and finish temperature. In applications, these materials must be trained in a special way to act as an actuator by constraining the material in a desired shape which in turn become the hot or parent shape, and heat treat at elevated temperatures together with using appropriate heat treatment time [5].

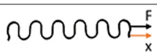
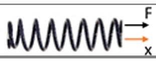
After the heat treatment process, depending on the heat treatment conditions, SMA exhibits twinned monoclinic lattice structure and stays below the Martensite finish temperature. When a stress is applied to the material under the same temperature condition, the material will strain by changing the lattice structure to the detwinned Martensite. In the instance where the applied stress is removed, material undergo permanent deformation. Increasing the temperature of the material beyond Austenite final temperature would cause recovery of the permanent strain and revert to its parent shape by changing to Austenite phase which shows a cubic lattice structure. Cooling the material would transform Austenite to twinned Martensite. This phenomenon is known as Shape Memory Effect (SME). If the temperature of the material is kept beyond the Austenite final temperature, it would behave super elastically and this scenario is known as Pseudo Elasticity (PE) [6]. SME and PE are considered as the key properties which makes the SMA promising in many applications.

According to the application, mentioned transformation temperatures can be altered to operate in application specific temperature bands. In order to account for the transformation temperatures, shape setting operation should be followed with a technique of investigating transformation temperatures. Among the different transformation temperature measuring techniques [7], Differential Scanning Calorimetry (DSC) can be used as a reliable method of investigating characteristic temperatures, because of its high sensitivity in measurements. Among many types of actuator configurations, linear type actuator was selected to use in the mentioned application area. Considering linear actuators for MIS tools, force and stroke capabilities are important. Table 1 justifies the selection of the actuator type used in this work as the spring shape produces high strokes and high forces compared to the other two types.

In this paper, fabrication of a SMA based spring actuator is discussed highlighting the shape setting operation carried out to develop the spring actuator. The resulting transformation temperatures were evaluated by DSC. Furthermore, an elemental analysis was conducted using Energy-dispersive X-ray Spectroscopy (EDX) technology to investigate the composition of the SMA material that has been used for the experiments. The developed actuator elements were tested through a specially developed gripper mechanism [8] which was manufactured using conventional machining and rapid prototyping techniques.

There are many avenues to apply SMA based actuator elements in the Minimally Invasive Surgical Field (MIS) [9]. Laparoscopic surgery has been the most significant advancement in endoscopic surgery which is a sub category of MIS. For such kind of applications, SMA based approach is more suitable to purposely design instruments which will overcome the limited degrees of freedom caused by the minimal invasiveness [10] of the surgical procedure. Devices made out of SMAs allow surgeons to perform complex surgical tasks. The purpose of the fabricated gripper is to facilitate laparoscopic surgical procedure. A gripper testing mechanism is discussed at the end as a case study to evaluate the performance of the gripper prior applying to the real scenario.

Table 1. Types of linear actuators.

Actuator type	Wire 	Wave 	Spring 
Stroke	Moderate	High	High
Force	Low	Moderate	High

2 Design of the NiTiNOL Spring Actuator

The most common commercially available SMA is named as NiTiNOL and it is a binary alloy comprising of Ni and Ti elements in specific weight percentages. The spring actuator was made out NiTiNOL wire material. The parameters of the spring are shown in Fig. 1. Since the raw NiTiNOL material was obtained in the form of wires (d = 1 mm), to form the helical shaped spring would require a specially developed fixture which holds the material while shape setting operation being carried out at elevated temperatures.

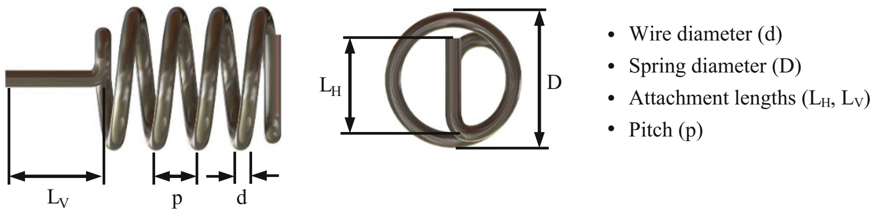


Fig. 1. NiTiNOL spring parameters.

3 Design of the Spring Forming Fixture

The NiTiNOL raw material was cold worked in the form of straight wires when they are being manufactured. Heat treating to a spring shape would require a fixture (see Fig. 2) which holds the wire without straightening. The fixture comprises a helical groove to support the wire to stay in a spring shape. Final spring would have two different attachment lengths at the two ends. The Vertical Attachment Length (VAL – L_V) was aligned with the axis of the spring by a positioner. The Horizontal Attachment Length (HAL – L_H) was formed by guiding through a hole located perpendicular to the axis of the fixture. The spring was then constrained by a sleeve in order to hold its shape during the heat treatment process.

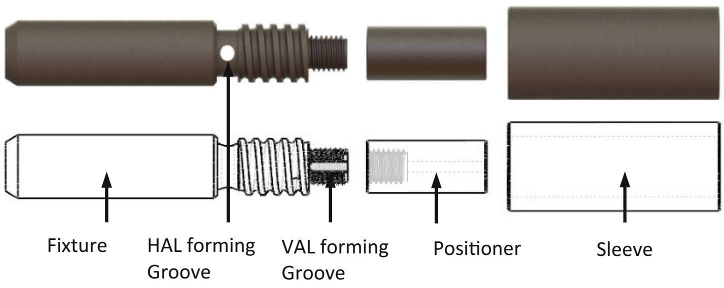


Fig. 2. NiTiNOL spring forming fixture.

4 Fabrication of the NiTiNOL Spring Actuator

4.1 Manufacturing of the Spring Forming Fixture

Material selection for the spring forming fixture is important because, cooling of the SMA actuator after the heat treatment process is mainly dictated by the fixture material. At the same time the material should have low thermal expansion co-efficient and should withstand for increased number of thermal cycles.

The material for the Fixture is AISI 1010 Carbon Steel and conventional Lathe machining was selected as the manufacturing process to fabricate the fixture. Table 2 gives a summary of the parameters needed to have in the final spring shape. Size of the fixture dictates the heat treatment process of the SMA material and in turn affects the induced transformation temperatures.

Table 2. Spring parameters.

Parameter	d	D	p	L_H	L_V
Value (mm)	1	7.5	2.5	6.5	10

4.2 Process of Constraining NiTiNOL Wire in the Fixture

A gauge of 1 mm NiTiNOL wire was used in the actuator development and initially it possesses considerable amount of bending resistance, as it is bent beyond a certain radius of curvature. Therefore, winding straight wire in to a spring shape would require a special technique (see Fig. 3).

4.3 Shape Setting Process of the NiTiNOL Spring Actuator

Shape setting operation was carried out in a Muffle furnace at elevated temperatures [3]. Transformation temperature mainly depends on the composition of the NiTiNOL material, Heat treating temperature and time. Since the composition is assumed to be uniform throughout the material, the required transformation temperatures were achieved by changing the heat treatment temperature and the time. 600 °C and 30 min were selected as the heat treatment temperature and the aging time respectively during shape setting of NiTiNOL springs.

5 Transformation Temperatures of NiTiNOL Springs

Following the above discussed heat treatment method for the spring actuator, it is clearly evident that the transformation temperatures may change and a clear measurement should be done by DSC. The technique monitors the energy changes happening within a sample under heating or cooling cycles. It measures the heat flow in to and out of the samples against a reference.

Transformation from Martensite to Austenite absorbs heat to progress endothermic reaction. It shows a dip in the heating curve. When cooling, the transition from Austenite to Martensite expels heat to progress exothermic reaction and it shows a peak in the cooling curve. The starting and end points of the dips and peaks correspond to the transformation temperatures of the SMA material (see Fig. 4). DSC 25 equipment developed by TA Instruments was used to investigate the transformation temperatures of the spring samples.

DSC plot depicts the heat flow rate w.r.t. scanning range chosen for the samples. Here the scanning range was 0 to 100 °C at a scanning rate of 3 °C/min. TZero Aluminum pans were used as the sample and reference pans and Nitrogen was used as the purge gas at 50 cm^3/min. Table 3 summarizes the results of obtained transformation temperatures by the DSC test conducted for the sample of heat treated spring actuator.

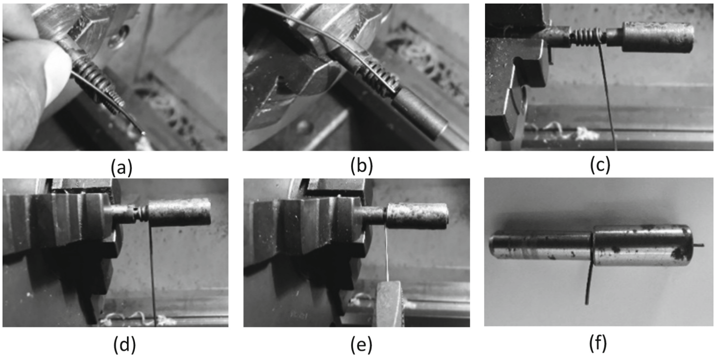


Fig. 3. Raw NiTiNOL wire fixing method: (a) positioning the VAL; (b) tightening VAL by the positioner; (c) winding the wire; (d) constraining by the sleeve; (e) tightening the sleeve; (f) wire and the fixture before shape setting.

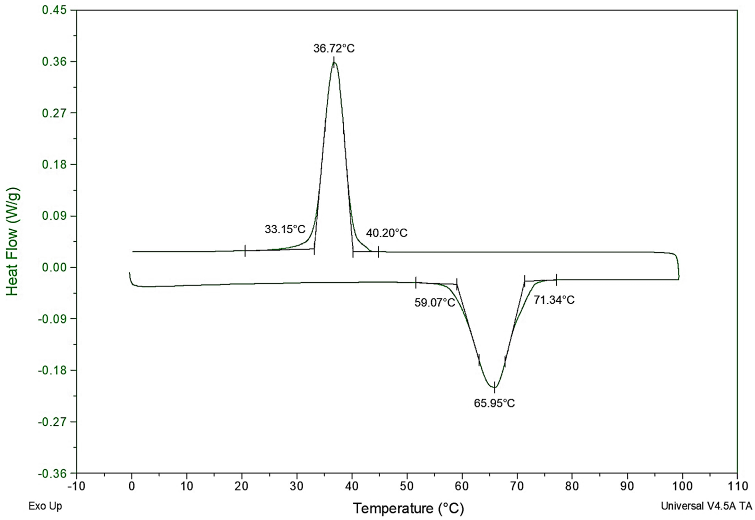


Fig. 4. DSC thermogram.

Table 3. DSC results.

A_s (°C)	A_f (°C)	M_s (°C)	M_f (°C)
59.07	71.34	40.20	33.15

6 Elemental Analysis by EDX Method

The alloying element content was obtained through an elemental analysis performed using a Scanning Electron Microscope (SEM) (ZEISS EVO|18 Research SEM). It has the capability to perform EDX analysis to find out the alloying compositions. Figure 5 depicts the EDX spectrum and the magnified view of the analyzed area of the NiTINOL sample.

So, it can be concluded that the commercially purchased material sample for testing, only contain Ni and Ti having Ni – 53.08% and Ti – 46.92% as weight percentages.

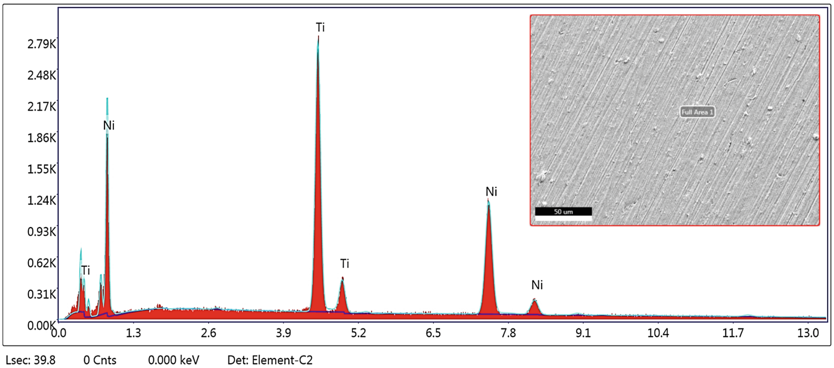


Fig. 5. EDX spectrum of NiTiNOL sample and the analyzed area at 1000×.

7 Development of SMA Spring Actuated Gripper

The developed NiTiNOL spring actuator was tested with a specially developed gripper mechanism which was activated through hot and cold fluid streams. The gripper was manufactured as two separate parts. One is the actuator structure and the other part being the gripper jaws and support structure.

7.1 Development of the Linear Actuator Structure

The design of the linear actuator which is discussing under this subsection is based on the developed SMA spring actuator element. The axial extension – compression motion assists for the stroke of the linear actuator (see Fig. 6). Linear actuator was designed as a piston–cylinder configuration and the SMA spring element is located inside the cylinder. At one end, there is an end cap which is threaded to the cylinder. VAL of the SMA spring passes through a hole whose axis is collinear with the cylinder axis located at the mount 2 which is threaded to the end cap. VAL is fixed at the mount 2 by the SMA attachment bolt 1. The HAL of the SMA spring passes through a hole perpendicular to the cylinder axis which is located at the mount 1. It is fixed to the mount 1 by the SMA attachment bolt 2. The mount 1 is threaded to the piston as shown in the Fig. 6. Also, there are two fluid I/O nozzles threaded to the cylinder body to transfer SMA activation fluid medium in to and out of the cylinder.

Fabrication process of the linear actuator was carried out by utilizing conventional machining techniques. Primarily, lathe machines were used to perform the turning, facing and thread cutting operations related to manufacturing of almost every components

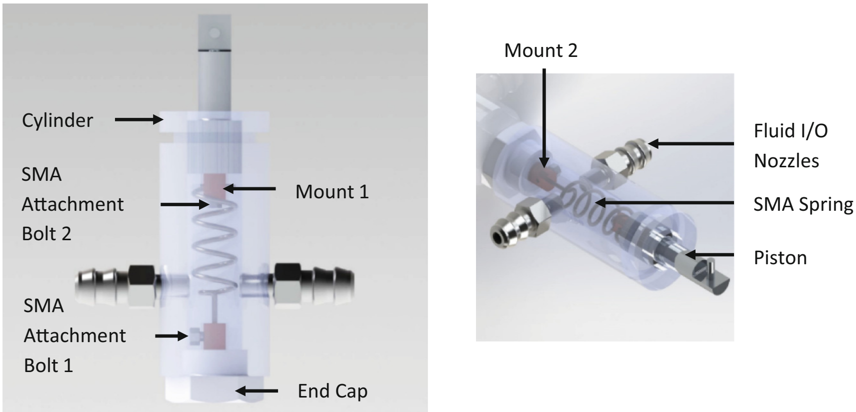


Fig. 6. Conceptual design of the linear actuator.

depicted in the Fig. 7. As the activating medium of the SMA element is a fluidic medium, a leak proof assembly of the components is highly important to make an efficient fluid flow and a heat energy transfer. All the threaded components are less susceptible to leak after assembly compared to the cylinder–piston sliding contact. So, a precise machining must be performed to obtain a leak proof but sliding joint. A close running fit was used to define the tolerances for piston and cylinder dimensions which are in the interest. According to the design of the linear actuator, piston is subjected to repetitive back and forth movement while producing the stroke. Hence, should be manufactured with a material having lower density in turn provide parts with less weight. This reduces the inertia of the piston and supports for efficient force transfer to the environment. So, the piston was manufactured using Aluminum material. Brass was used to manufacture cylinder, mounts and the nozzles of the actuator. With the increase of temperature, Aluminum expands more than brass volumetrically and in turn results a more fluid tight connection between piston–cylinder prismatic joint while facilitating axial displacements. Steel was used to fabricate end cap part.

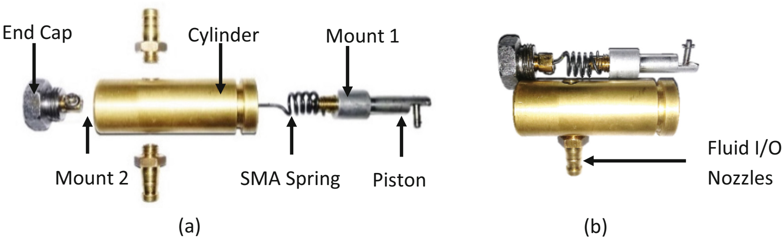


Fig. 7. Fabricated linear actuator: (a) exploded view; (b) half-assembled configuration.

7.2 Development of the Gripper Components

Figure 8 shows the components of the designed gripper mechanism. The linear motion of the piston was converted to an angular motion by the link which is hinged to the base structure. The link consists of two slots that limit the motion and two pins that connect the piston and the driver jaw. The slots were designed in a manner in which no sudden lockups will occur. The rotational motion of the link is transferred to the driver jaw by the reaction force between the pin and slot joint which makes the jaw rotate around a hinge that is located at the base. In order to compact the mechanism, the gripper pair was connected through a sector gear pair. The main two actuation elements are the SMA spring and the steel torsion spring which support the opening and closing of the gripper jaws respectively. Top cover, bottom cover and the gripper jaws (see Fig. 9) were made out of one of the rapid prototyping technique. (i.e.: 3D printing) The material that was used to manufacture these components is Acrylonitrile Butadiene Styrene (ABS) Plus and it provides promising specific strength (strength to weight ratio = 39–43 kN.m/kg) compared to the other 3D printing materials. The Link was made out of poly methyl methacrylate (PMMA) or commercially named as Perspex by Laser cutting technique. Torsional spring was made out of 1 mm steel wire by using a spring forming machine.

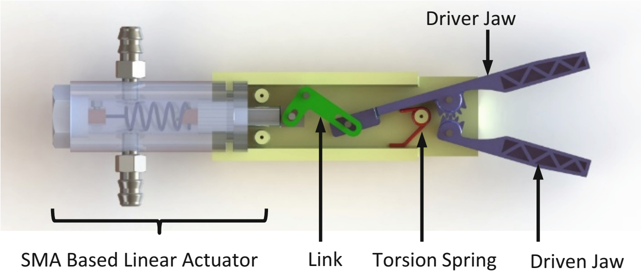


Fig. 8. Conceptual design of the finalized gripper mechanism combined with the linear actuator.

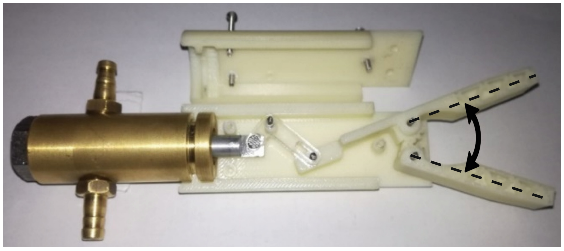


Fig. 9. Fabricated gripper components in assembly.

7.3 Development of the Testing Apparatus

The SMA spring actuated gripper [8] was used to validate the operation of NiTiNOL spring actuator when temperature is increased by controlling hot and cold fluid streams.

Linear motion of the piston happens when a temperature controlled fluid flow passes through the cylinder chamber. The linear motion of the piston converts to a gripping motion by the above mentioned mechanism. The cylinder chamber consists with two nozzles one for the inlet and one for the outlet (see Fig. 10). The inlet is connected to the hot and cold fluid pumps and the outlet is connected to a fluid collector. The hot fluid source is maintained at a desired temperature by a controller using its temperature control mode. The hot fluid source was maintained at a temperature of 80 °C.

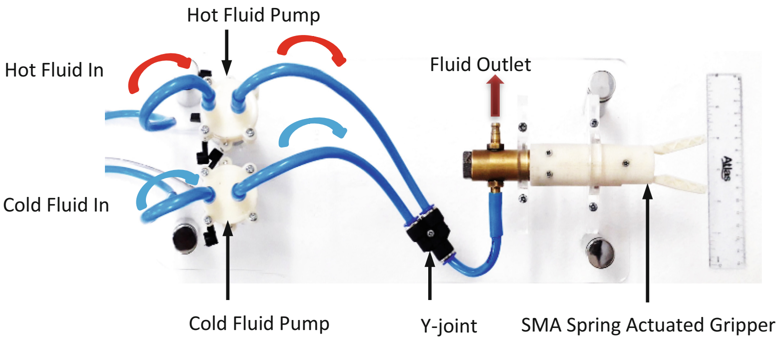


Fig. 10. Component description and fabricated testing apparatus.

8 Sustainability in SMA Based Actuation Techniques

According to the above discussed facts, it is evident that the SMA spring actuator operated under the temperature cycling and variation of induced stresses. This would cause structural and functional fatigue of SMA material [11]. But, not like other materials, SMAs enable the manufacturer a sustainable solution by providing recovery characteristics of functional fatigue facilitating reusability of the actuator elements. This is possible as the fatigued actuators are periodically annealed by heating above the Austenite final temperature. It will retransform the residual martensitic phases in to parent phase enhancing the fatigue life [12]. This is a huge advantage in terms of sustainable aspects in manufacturing.

9 Conclusion

An SMA actuator was designed and developed which was activated through fluid heating and cooling. A Novel fixture was designed to facilitate the heat treatment process of the NiTiNOL spring actuator. Furthermore, the heat treatment process and the resulting transformation temperatures were analyzed by DSC technique. Since, the transformation temperatures also depend on the material composition, an EDX analysis was conducted to account for the SMA material composition and found out selected samples contain Ni – 53.08% and Ti – 46.92% as weight percentages. A gripper was designed and developed using conventional machining techniques and rapid prototyping methods. Finally, the spring actuator was successfully tested using an apparatus. The closing and opening motion of the gripper could be successfully achieved by controlling hot and cold fluid sources respectively. So, the SMA based actuation is possible for Laparoscopic grippers and further improvements need to be done in the areas of optimized controlling and device miniaturization. Also, SMA material enables sustainability in manufacturing smart actuators for bio medical applications as it possess the capability of healing from functional fatigue.

References

1. Mohd Jani, J., Leary, M., Subic, A., Gibson, M.A.: A review of shape memory alloy research, applications and opportunities. Mater. Des. 1980–2015 **56**, 1078–1113 (2014). https://doi.org/10.1016/j.matdes.2013.11.084
2. Kocich, R., Szurman, I., Kursa, M.: The methods of preparation of Ti-Ni-X alloys and their forming. IntechOpen (2013). https://doi.org/10.5772/50067
3. Miller, D.A., Lagoudas, D.C.: Influence of cold work and heat treatment on the shape memory effect and plastic development of NiTi. Mater. Sci. Eng. A **308**(1–2), 161–175 (2001). https://doi.org/10.1016/S0921-5093(00)01982-1
4. Jardine, A.P.: Calorimetric techniques for the evaluation of thermal efficiencies of shape memory alloys. J. Mater. Sci. **24**(7), 2587–2593 (1989). https://doi.org/10.1007/BF01174530
5. Liu, X., Wang, Y., Yang, D., Qi, M.: The effect of ageing treatment on shape-setting and superelasticity of a nitinol stent. Mater. Charact. **59**(4), 402–406 (2008). https://doi.org/10.1016/j.matchar.2007.02.007
6. Ziółkowski, A.: Pseudoelasticity of Shape Memory Alloys Theory and Experimental Studies. Butterworth Heinemann, Oxford, UK (2015)
7. Abel, E., Luo, H., Pridham, M., Slade, A.: Issues concerning the measurement of transformation temperatures of NiTi alloys. Smart Mater. Struct. **13**(5), 1110 (2004). https://doi.org/10.1088/0964-1726/13/5/016
8. Roshan, T.A.U., Amarasinghe, Y.W.R., Dayananda, N.W.N.: Design and development of a shape memory alloy spring actuated gripper for minimally invasive surgeries. B-Con Plaza, Beppu, Oita, Japan, pp. 566–569. Feb 2018. https://doi.org/10.5954/ICAROB.2018.OS14-5
9. Song, C.: History and current situation of shape memory alloys devices for minimally invasive surgery. Open Med. Devices J. **2**, 24–31 (2010)
10. Roshan, U., Amarasinghe, R., Dayananda, N.: Design and fabrication of a minimally invasive surgical device with customized shape memory alloy spring actuator. J. Robot. Netw. Artif. Life **5**(3), 194–198 (2018). https://doi.org/10.2991/jrnal.2018.5.3.11
11. Mammano, G.S., Dragoni, E.: Functional fatigue of NiTi shape memory wires for a range of end loadings and constraints. Frat. Ed Integrità Strutt. **7**(23), 14–33 (2013). https://doi.org/10.3221/IGF-ESIS.23.03
12. Wagner, M.F.-X., Nayan, N., Ramamurty, U.: Healing of fatigue damage in NiTi shape memory alloys. J. Phys. Appl. Phys. **41**(18), 185408 (2008). https://doi.org/10.1088/0022-3727/41/18/185408

3D Printed Multi-channel Peristaltic Pump with Active Droplet Generator for Lab-on-a-Chip Devices

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Abstract. This paper presents the development of a multi-channel peristaltic pump using 3D printing technology for active droplet generation. The fabricated peristaltic pump has two channels with 3 mm diameter to pump two different fluids simultaneously. Final assembly of the multi-channel peristaltic pump is 146 mm in length, 230 mm in width and 75 mm in height. Numerical studies are conducted using COMSOL Multiphysics software to study the droplet formation under the peristaltic motion. Experiments on droplet generation are carried out using in-house fabricated peristaltic pump and the droplet generator. From and the numerical simulations and the experiments, it was identified that the use of the peristaltic motion for the dispersed phase fluid is capable of forming droplets.

Keywords: Multi-channel peristaltic pump · 3D printing · Droplet microfluidics · Active droplet generation

1 Introduction

In recent years, the field droplet microfluidics has been continuously growing due to its attractive features such as small sample consumption, fast mixing and digitalization which avoids cross contamination between different samples [1]. Droplet generation is used in wide range of microfluidic applications as it can produce monodisperse droplets while controlling each droplet that can facilitate fast reaction [2]. Lab-on-a-chip (LOC) and micro total analysis systems provide great benefits to the conventional laboratory analysis methods and techniques [3]. LOC devices miniaturize the biological and chemical analysis processes. Clinical diagnostics, food and environmental analysis and drug discovery are few application areas of LOC devices. As a key aspect in LOC devices, droplet generation allows to conduct controlled and rapid mixing of fluids. Due to the ability of droplets to use as individual reactors and to the high throughput nature of the droplet microfluidics, it has been highly applied in biomedical research. Various practical problems such as pumping has restricted the growth of microfluidic solutions to perform laboratory functions [4]. Mechanical approaches are often simple and well

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suited to establish test platforms and assays which can benefit from fluidic activation [5]. Non-contact type pumps are one such mechanical pump that can pump the fluid without any contamination.

Non-contact type pumps are widely used in medical applications to transport fluid without any contaminations [6]. Peristaltic pump is one such non-contact pump which can provide contamination free liquids with better accuracy and flow control [7, 8]. Peristaltic pump is a positive displacement pump where fluid is contained within a flexible tube fitted in a circular pump casing [9]. A rotor with rollers, wipes or shoes attached to external circumference compresses the flexible tube thereby transporting the fluid volume trapped between the adjacent rollers.

Conventional manufacturing use material removal or mold based formative techniques to produce desired products [10]. These techniques require costly infrastructure and multiple steps such as creating a mold and then removal of unwanted material. Therefore, the cost effectiveness, the timeliness and the fabrication of complex geometrical features using the conventional manufacturing techniques have been limited. 3D printing or additive manufacturing has evolved over the past few decades addressing the above-mentioned issues of conventional manufacturing techniques. 3D printing is based on the principle of layered manufacturing, where materials are overlapped layer by layer in three-dimensional space guided by computer generated model [11]. Due to the improved printing precision and speed, it has shown a great potential in medical industry for the fabrication of medical equipment, surgical implants, surgical guides, external aids and bio-manufacturing [12]. Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are commonly used additive manufacturing techniques used in biomedical applications [13].

In this research, an active droplet generation system is studied using an in-house fabricated pump based on peristaltic motion. The multi-channel peristaltic pump is designed and fabricated using FDM technology of 3D printing.

2 Proposed System

With relation to on-chip technology, droplet generation plays a major role in applications such as drug development, pathology testing, and chemical reactions. Droplet generation methods are mainly categorized into passive and active methods. In the passive method the droplets are formed without an additional energy input whereas in the active method an external actuation is used to generate droplets. Droplet diameter and the formation frequency are the two major parameters considered in utilization of a droplet generator for specific applications Active droplet generation systems provide the flexibility of controlling the droplet production and manipulation through electrical, magnetic, or centrifugal forces. As shown in Fig. 1, the proposed microfluidic active droplet generation system consists of a multi-channel peristaltic pump and controller, submersible pump and controller, droplet generator, two reservoirs, and a computer. The peristaltic pump is proposed to generate a microflow of the dispersed phase and the submersible pump is to pump the continuous phase.

Two important aspects considered in developing an active microfluidic droplet generation system are the pumping mechanism and the droplet generation geometry. Thereby,

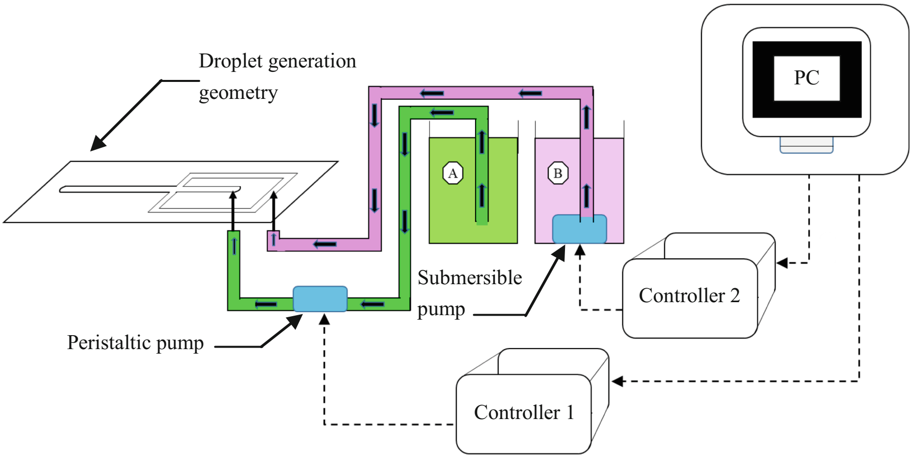

Fig. 1. Proposed system.

peristaltic motion based mechanism is studied in the proposed system having a flow-focusing geometry for droplet generation. The droplet generator design with flow-focusing geometry is shown in Fig. 2. The inlet – A is for the dispersed phase fluid and the inlet – B is for the continuous phase fluid. The droplet generation process starts to take place at the contraction and the generated droplets are channeled through the cavity that terminates at outlet – C. The optimization of the dimensions using numerical analysis for the droplet generator design is discussed in a previous work [14].

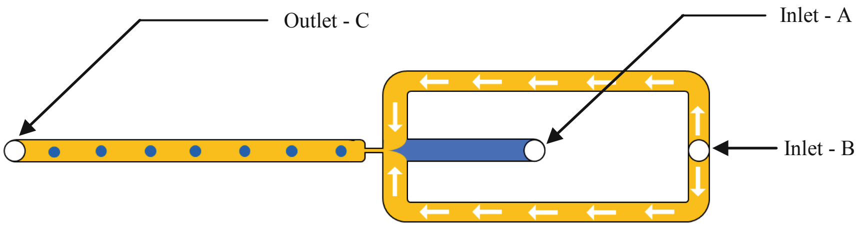

Fig. 2. Flow-focusing droplet generator geometry.

In flow-focusing geometry of droplet generation, the two fluids are met at the contraction and when the applied shear stress from the continuous phase fluid on the dispersed phase is greater than the viscosity, dispersed phase flow breaks into small fluid particles, forming droplets.

3 Design and Simulation

SOLIDWORKS software is used to design the peristaltic pump. The pump consists of three rollers which are used to press the two flexible tubes, a pump base which guides the two flexible tubes, two roller holders, and a stepper motor which helps to rotate the

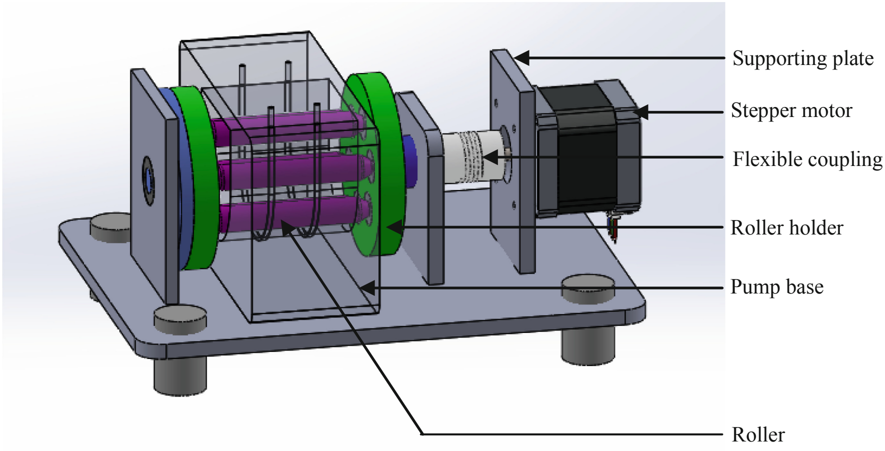

Fig. 3. Proposed design of the multi-channel peristaltic pump.

roller holders with three rollers via a flexible coupling. Figure 3 shows the designed model of the peristaltic pump and the components.

The theoretical flow rate of a peristaltic pump shows a linear behaviour with the angular velocity of the motor. The following equation shows the relationship between the theoretical flow rate with the parameters that influence the flow rate of the peristaltic pump.

$$Theoretical\ flow\ rate = A \times L \times N \times \omega \tag{1}$$

Whereas 'A' is the area of the tube, 'L' is the tube length occluded by rollers, 'N' number of rollers and 'ω' is the angular velocity in rounds per minute (rpm). Two intravenous lines (IV) which have 3 mm of inner diameter was used as the tubes for the two channels. The radius of the curvature is 24 mm and therefore the occluded length can be calculated from Eq. (2).

$$Occluded\ length = 2 \times \pi \times Tube\ radius\ of\ curvature \times \frac{Angle\ between\ two\ rollers}{360^{\circ}} \tag{2}$$

The three rollers are placed at an angle of 120° between each of them. Therefore, the occluded length of the tube due to the rollers is 50.27 mm. From Eq. (1) it can be concluded that the theoretical flow rate of a single channel in the designed multi-channel peristaltic pump has the following pump characteristic with the angular velocity of the motor.

$$Theoretical\ flow\ rate = 4.26 \times \omega \ \cdot ml/min \tag{3}$$

The simulations are conducted using COMSOL Multiphysics software to identify the droplet generation ability of the system. In this study, conservative level set method of modelling two phase flows is used to observe the effect of a peristaltic motion applied to the dispersed phase fluid, on droplet generation. Water is used as the dispersed phase

Table 1. Physical properties of the selected fluids

Phase	Liquid	Density (kg/m^3)	Viscosity (cP)
Dispersed phase	Water	1000	1.01
Continuous phase	Coconut oil	900	55

liquid and coconut oil is used as the continuous phase. The physical properties for the selected fluids are shown in Table 1.

In the simulation, peristaltic motion is introduced to the dispersed phase while the continuous phase fluid flow velocity is set as a constant value and the outlet pressure is set to zero.

4 Fabrication

Two major manufacturing techniques are used in developing the droplet generation system with the multi-channel peristaltic pump. Most components of the multi-channel peristaltic pump are fabricated using 3D printing technology while the supporting structure and the layers of the droplet generator are fabricated using laser machining technique.

4.1 Multi-channel Peristaltic Pump

Manufacturing using conventional subtractive, or mold based formative methods are expensive due to the requirement of specialized equipment such as Computer Numerical Control (CNC) machines, injection molding machines or separate mold for each component. In contrast, in additive manufacturing techniques materials are deposited layer upon layer to obtain the geometrical shape of the design. Compared with the conventional manufacturing with precision machining and molding costs, it is obvious that the 3D printing with three axis motorized controller can fabricate the components with required tolerances with lower cost.

Polylactide (PLA) and Acrylonitrile Butadiene Styrene (ABS), are the most common thermoplastic material used in Fused Deposition Modelling (FDM) technology based 3D printing. Among the above two materials, PLA consists of renewable raw materials, and it also presents the advantage of being biodegradable. The enhanced type of a PLA, which is PLA+ includes other plastics, additives or pigments that assists in improving the performance of standard PLA by reducing the moisture absorption and brittleness. The fabrication of the components of the multi-channel peristaltic pump is done with a FDM based 3D printer using PLA+ as the filament. During the fabrication process, the 3D printer bed is kept at 60 °C and the extruder is heated up to 200 °C for the filament to melt and a 90% infill with the zigzag pattern is used for all the components. Furthermore, the printing speed is kept at 60 mm per second with a layer height of 0.1 mm and wall thickness of 3 mm. Figure 4. shows all the components fabricated using 3D printing.

Supporting plates and the bottom holder of the peristaltic pump assembly are fabricated using laser machining. 5 mm Polymethylmethacrylate (PMMA) sheets are used for

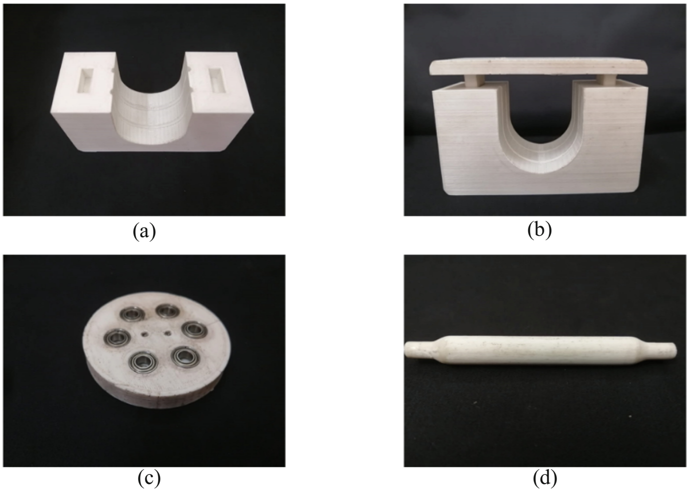

Fig. 4. 3D printed components of the pump (a) Base; (b) Base with the lid; (c) Rotor; (d) Roller.

three supporting plates and the bottom holder of the assembly. The laser beam diameter is set to 0.02 mm, the laser power is set to 35 W, the cutting speed is kept at 5 mm s^{-1} and the laser focus position is set to the top surface of the PMMA sheet in fabricating the supporting structures.

4.2 Droplet Generator

Design and fabrication of the droplet generator is carried out at an early stage of the research and a detailed description of the fabrication process is presented [14]. It is fabricated using laser machining technology with solvent assistant bonding method to bind PMMA layers. Figure 5 shows the fabricated droplet generator.

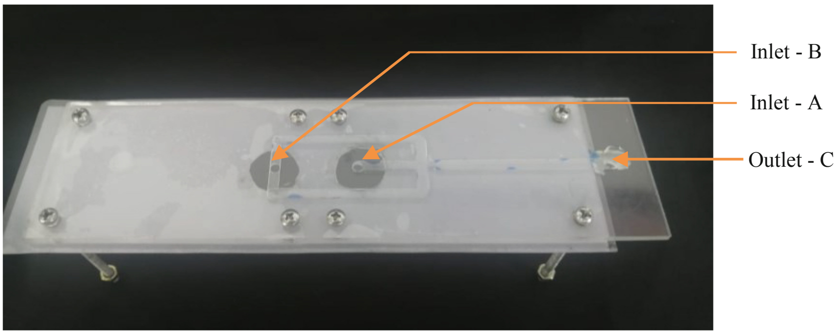

Fig. 5. Droplet generator.

5 Results and Discussion

In simulating the fluid flow generated by the peristaltic pump and the submersible pump, a peristaltic motion for the dispersed phase and a constant flow rate for the continuous phase is applied and this configuration successfully resulted in forming droplets and the sequence of droplet generation is shown in Fig. 6.

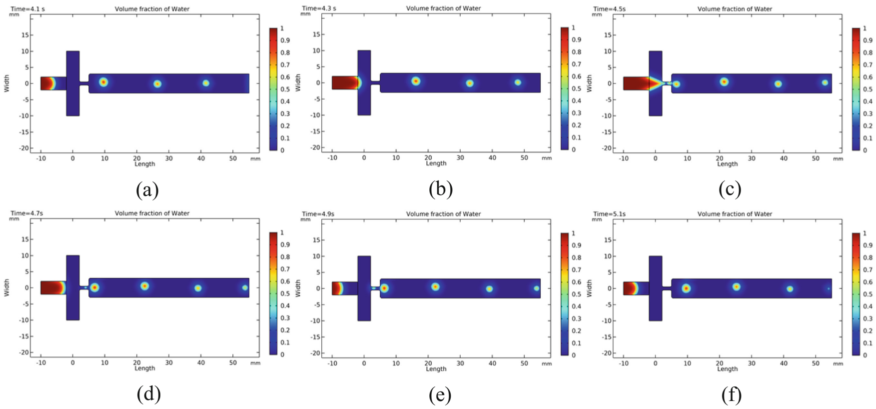

Fig. 6. Droplet generation sequence (a) At t = 4.1 s; (b) At t = 4.3 s; (c) At t = 4.5 s; (d) At t = 4.7 s; (e) At t = 4.9 s; (f) At t = 5.1 s.

Formation of droplets under the peristaltic motion occurs periodically. Therefore, the simulation results show that it is possible to achieve desired droplet diameters and droplet generation frequencies by altering the frequency and the amplitude of the peristaltic function. Afterwards, the fabrication of a peristaltic pump is studied to configure an experimental setup. The feasibility in fabricating the designed multi-channel peristaltic pump is evaluated among conventional, and additive manufacturing techniques and it is identified that the fabrication cost for 3D printing is less compared to other manufacturing techniques. Figure 7 shows the final assembly of the 3D printed multi-channel peristaltic pump.

The experimental procedure is carried out to evaluate the suitability of using a peristaltic pump for droplet generation in the fabricated droplet generator based on the flow-focusing geometry. Similar to the simulation, water is used as the dispersed phase fluid and coconut oil is used as the continuous phase fluid in testing. In-house fabricated peristaltic pump is used to pump the dispersed phase fluid and the submersible pump for the continuous phase fluid. In order to distinguish the fluid phases, colouring is added to the water as in the experimental setup shown in Fig. 8.

It is observed that the aforementioned experimental setup successfully performs droplet generation and the captured images during the experiment are shown in Fig. 9. During the experiment flow rate of the continuous phase and the angular velocity of the

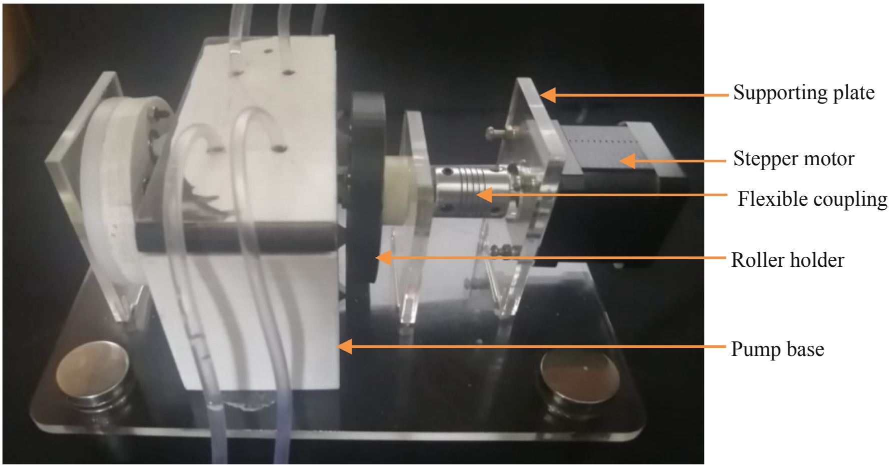

Fig. 7. Assembly of the fabricated multi-channel peristaltic pump.

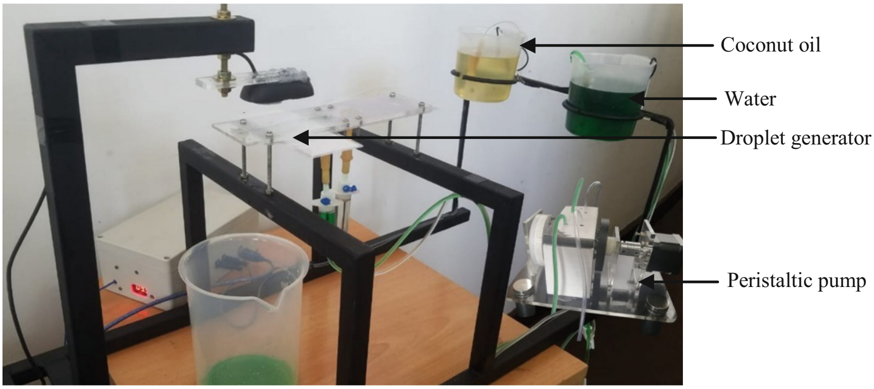

Fig. 8. Experimental setup.

stepper motor which actuates the peristaltic pump are kept constant. In this configuration the pulsating effect of the peristaltic pump is observed to be significant.

The diameters of the generated droplets are calculated based on the captured images using MATLAB and Rstudio software. The diameter of the generated droplets shows a variation throughout the experiment which is shown in Table 2. In addition, the droplet formation shows cyclic effect as the peristaltic pump has a pulsating effect when pumping the fluids.

The droplets formed between the time frame 4 s to 10 s are shown in Fig. 9(c) and the calculated diameters of the droplets are 1.02 mm, 0.71 mm, and 0.65 mm respectively.

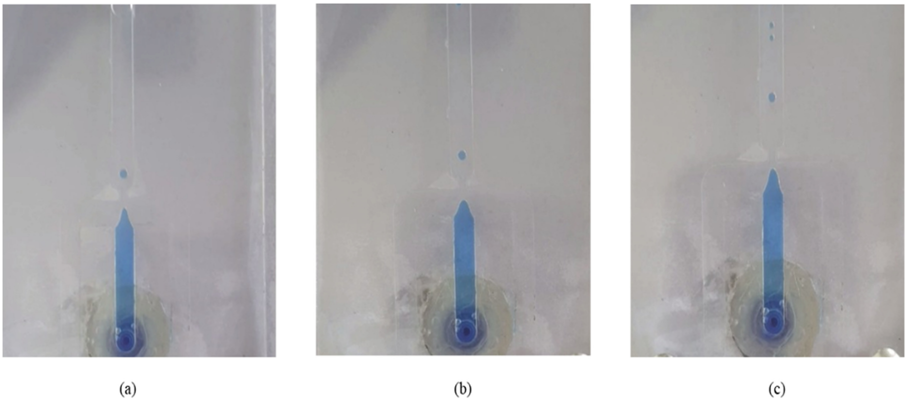

Fig. 9. Generated droplets at different time steps of the experiment (a) At t = 1 s; (b) At t = 4 s; (c) At t = 10 s.

Table 2. Diameter of the generated droplets

Time frame	Diameter
1 s	1.08 mm
4 s	1.16 mm
10 s	1.02 mm

6 Conclusion

In this research, an active droplet generation system is successfully developed using the in-house fabricated multi-channel peristaltic pump and a commercially available submersible pump. Use of a peristaltic pump for droplet generation is important for the fluids such as blood which should not be contaminated. Since the pump parts are not engaged with the transported fluid, it is suitable to pump biological fluids for analysis. Droplets are observed in simulations and in testing, which validates the capability of peristaltic motion based active methods in forming droplets. The multi-channel peristaltic pump is fabricated using FDM 3D printing technology and the fabrication process is comparatively cost-effective in manufacturing but obtaining a higher quality surface finish to precisely control the pump is harder than CNC machining. Based on simulation and experimental results, it is identified that due to the pulsating effect of the peristaltic pump, the formation of the droplets showed a cyclic effect with time. In minimizing the pulsating effect, more rollers can be introduced to the peristaltic pump. Additionally, it will assist in increasing the controllability of the system which is the most significant factor considered in active droplet generation related to LOC applications.

In future, utilization of both channels of the multi-channel peristaltic pump to pump dispersed phase and continuous phase fluids is to be implemented to observe the effect of two pulsating flows on droplet formation behaviour. Ultimately, the suitability of using peristaltic pumps for droplet generators which can be integrated into a LOC device can be evaluated.

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References

1. Chabert, M., Dorfman, K.D., Cremoux, P., Roeraade, J., Viovy, J.-L.: Automated Microdroplet Platform for Sample Manipulation and Polymerase Chain Reaction, Oct. 2006, https://doi.org/10.1021/ac061205e.
2. Dangla, R., Kayi, S.C., Baroud, C.N.: Droplet microfluidics driven by gradients of confinement. Proc. Natl. Acad. Sci. USA **110**(3), 853–858 (2013). https://doi.org/10.1073/pnas.1209186110
3. Culbertson, C.T., Mickleburgh, T.G., Stewart-James, S.A., Sellens, K.A., Pressnall, M.: Micro total analysis systems: fundamental advances and biological applications. Anal. Chem. **86**(1), 95–118 (2014). https://doi.org/10.1021/ac403688g
4. Laser, D.J., Santiago, J.G.: A review of micropumps. J. Micromech. Microeng. **14**(6), R35–R64 (2004). https://doi.org/10.1088/0960-1317/14/6/R01
5. Skafte-Pedersen, P., Sabourin, D., Dufva, M., Snakenborg, D.: Multi-channel peristaltic pump for microfluidic applications featuring monolithic PDMS inlay. Lab Chip **9**(20), 3003–3006 (2009). https://doi.org/10.1039/B906156H
6. Hettiarachchi, S.P., Pathirana, G.C.K., Perera, M.R., Amarasinghe, Y.W.R., Jayawardane, M.A.M.M., Dau, V.T.: Design and development of an automated fluid management system for endoscopy aided gynaecological surgeries. In: IOP Conf. Ser.: Mater. Sci. Eng., vol. 922, p. 012008, Oct. 2020, https://doi.org/10.1088/1757-899X/922/1/012008
7. Todorov, V., Aprahamian, B., Tahrilov, H. : Applicability of peristaltic pumps in installations for vegetable oils processing. In: 2016 19th International Symposium on Electrical Apparatus and Technologies (SIELA), pp. 1–4, May 2016, https://doi.org/10.1109/SIELA.2016.7543054
8. Berg, J.M., Dallas, T.: Peristaltic pumps. In: D. Li (ed.) Encyclopedia of Microfluidics and Nanofluidics. Springer US, Boston, MA, pp. 1626–1633 (2008)
9. Dhumal, S.R., Kadam, S.S.: Design and Development of Rotary Peristaltic Pump, vol. 2, no. 4, p. 7 (2012)
10. Ahangar, P., Cooke, M.E., Weber, M.H., Rosenzweig, D.H.: Current biomedical applications of 3D printing and additive manufacturing. Appl. Sci. **9**(8), 1713 (2019). https://doi.org/10.3390/app9081713
11. Yan, Q., et al.: A review of 3D printing technology for medical applications. Engineering **4**(5), 729–742 (2018). https://doi.org/10.1016/j.eng.2018.07.021
12. Javaid, M., Haleem, A.: Additive manufacturing applications in medical cases: a literature based review. Alexandria J. Med. **54**(4), 411–422 (2018). https://doi.org/10.1016/j.ajme.2017.09.003
13. Liu, Y., Wang, W., Zhang, L.-C.: Additive manufacturing techniques and their biomedical applications. Family Med. Commun. Hlth. **5**(4), 286–298 (2017). https://doi.org/10.15212/FMCH.2017.0110
14. Sampath, W.H.P., Hettiarachchi, S.P., Melroy, N.H.R.G., Amarasinghe, Y.W.R.: Design and development of a droplet-based microfluidics system using laser fabrication machining techniques for a lab on a chip device. In: Y.-W. Chen, S. Tanaka, R.J. Howlett, L.C. Jain (eds.) Innovation in Medicine and Healthcare, vol. 192, pp. 201–210. Springer, Singapore (2020). https://doi.org/10.1007/978-981-15-5852-8_19

Barriers to Transitioning Towards Smart Circular Economy: A Systematic Literature Review

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Abstract. This paper defines smart circular economy as an industrial system that uses digital technologies to implement circular strategies such as reduce, reuse, remanufacturing and recycling. The smart circular economy has been regarded as a promising approach to enhance sustainability. However, barriers exist in various stages of the transition towards smart circular economy. This paper employs a systematic literature review to identify the main barriers that prevent companies from this transition. We adopt a change management perspective to study this transition and propose that it follows a classical three-step process of organizational change: unfreeze, move, and refreeze. We identified 24 barriers in five categories: finance, management, infrastructure, network, and technology. Then, we placed the barriers into the three steps to further investigate how they affect each stage of the transition. Our analysis suggests that: (a) stakeholders play a central role in the process; (b) companies often have financial issues in the early steps of change; (c) technological challenges emerge in the advanced steps. The findings can help diagnose companies' current status, identify solutions to tackle the barriers and predict future challenges.

Keywords: Smart circular economy · Sustainability · Digitalization · Change management · Barriers

1 Introduction

Circular economy (CE) is an industrial system that reduces and reuses productive resources taking into account environmental, economic, and social impacts [1, 2]. It stands out as a sustainable alternative to manufacturers that extract raw materials from nature and discard the waste [3]. The concept can be translated into circular strategies like the 9Rs proposed by Potting et al. [4]. These strategies can be enabled and potentialized by digital technologies (DTs) such as internet of things and big data [5].

We define smart circular economy (SCE) as *an industrial system that uses DTs to provide intelligent functions for implementing value-added circular strategies*. For

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example, data collection and analysis can be automated by the internet of things and advanced alghoritms. This intelligent function enable failure prediction and preventive maintenance, which are strategies to improve resource efficiency [6–8]. In short, it is a system that uses DTs to foster circularity.

Recently, research has focused on the early stages of CE transition, such as identifying opportunities and designing business models (BMs) [9]. Topics related to implementing organizational change, such as business strategy and management models, are rarely discussed [10]. However, to succeed in the transition, organizational aspects are as relevant as conceptual and technological development. To address this problem, this paper takes a comprehensive view of organizational transformation provided by change management theory. It has been widely adopted to analyse CE transition [11], and we extend this importance to the SCE.

Incorporating DTs generates new barriers to the transition towards a circular system. It conflicts with other business factors, like costs, and results in new business challenges, such as data management [12]. This topic has received wide academic interest, but there is still little consensus. Most of the results from articles cannot be generalized since they analyze specific sectors and countries. The comparison is difficult because the nomenclature of barriers is not standardized, and the papers differ in research methodology.

Therefore, this paper provides a review of the previous studies to built comprehensive knowledge about barriers to the SCE. This work aims to analyze publications on the topic to answer the research question: ***What are the main barriers at each stage of the transition towards SCE?***

The remainder of this paper is structured as follows. Section 2 describes the research methods. Then, Sect. 3 presents the results and discussion. Some final remarks are summarized in Sect. 4.

2 Research Methods

We conducted a systematic literature review (SLR) [13]. This methodology results in a theoretical model based on the information accumulated by previous studies. It is an explicit and rigorous process. It prevents the author's bias from hampering understanding the topic and allows practitioners and other researchers to use the results. Each stage is described below to ensure the transparency and reproducibility of this research.

2.1 Selection of Publications

The first stage focused on identifying relevant publications. The selection was conducted between November and December 2020. Scopus and Web of Science databases were chosen due to their coverage of academic articles. Only journal and conference papers were included to ensure reliability and to reduce publication bias [14]. Exclusion criteria related to language and year of publication were unnecessary, as all articles were in English and have been published in recent years.

Figure 1 shows an overview of the process, including the number of the remaining papers at each SLR stage. Titles and abstracts were examined to identify relevant works based on two inclusion criteria. Finally, we read the full text of the selected publications and excluded those without any specific barriers to the SCE.

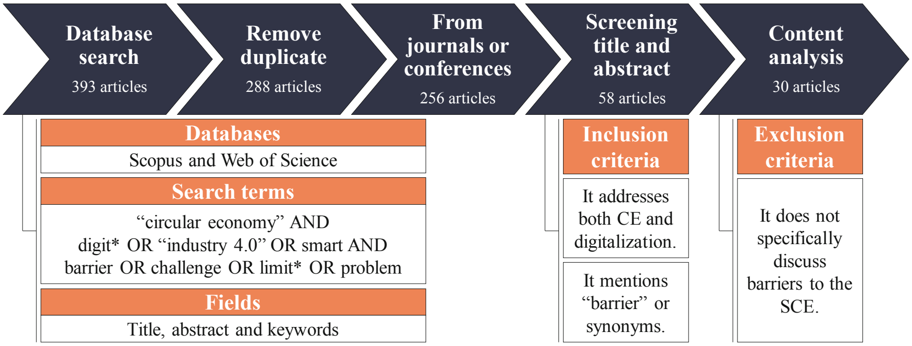

Fig. 1. Methodological procedure.

2.2 Content Analysis

The second stage focused on extracting and analysing data from the articles. We used MAXQDA software to support the process and conduct the qualitative data analysis [15]. We coded the relevant segments and merged them according to their content (e.g., barriers related to the definition of parameters and the quality of the data collected was coded as "lack of data collection skills").

To understand how barriers affect the SCE transition, we placed them in a change management model. We chose Lewin's three-step model [16] because it is well-recognized as the main model compared to other 15 classical change approaches [17]. This model describes the mechanism of change for different social contexts, not only for organizational cases [16, 18]. The results are presented in Subsects. 3.1 and 3.2.

3 Results and Discussion

3.1 Selected Sample and Identified Barriers

The final result of paper selection consists of 30 publications from 2016 to 2021. Of these articles, 10 were published in 2019 and 12 in 2020. The "Resources, Conservation and Recycling" and "Journal of Cleaner Production" were the most relevant journals, with four and three publications respectively. In half of these articles, the first author is affiliated with an European institution. Survey and interview were the most favourable research method, adopted in 15 articles.

Regarding the barriers to the SCE, we identified 24 relevant barriers that have prevented the transition. To ensure that only relevant barriers were taken for analysis, each barrier should be mentioned at least by three different articles. They were grouped

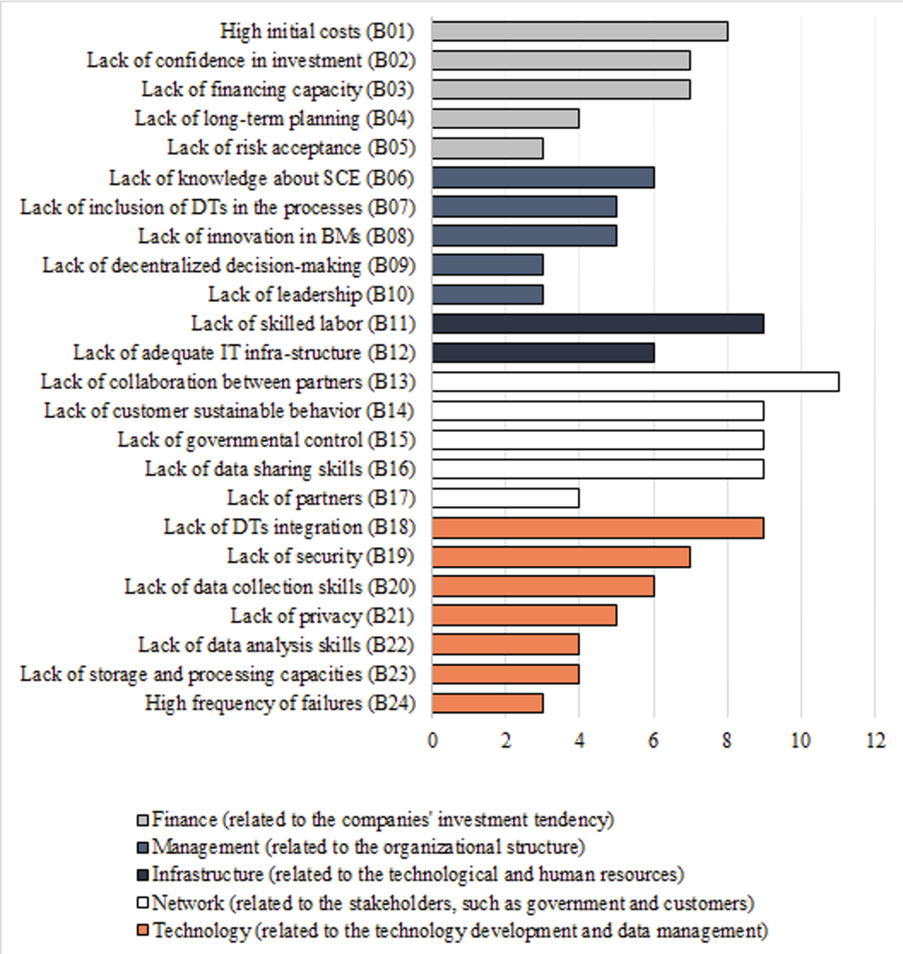

Fig. 2. Number of publications per mentioned barrier.

into five categories (see Fig. 2): finance, management, infrastructure, network, and technology.

The "network" category is the most mentioned in literature and it indicates that individual goals depend on stakeholders. This finding is in line with the idea that circularity requires a system change, and it cannot be achived by one company alone [19]. Other relevant barriers are lack of skilled labor (B11), a problem that has mainly concerned in emerging markets [20–22], and lack of DTs integration (B18), which is due to the incompatibility of various DTs. A description of each barrier is provided in Table 1.

3.2 Barriers at Three-Step Change Model

As described in Subsect. 2.2, we adopted the three-step change model [16] to analyze the barriers. The result is shown in Fig. 3.

Table 1. Barriers to transitioning towards SCE.

Category	Code	Name	Description	References
Finance	B01	High initial costs	The need to develop technology and skilled labor can lead to prohibitive implementation costs	[12, 21, 23–28]
	B02	Lack of confidence in investment	High initial costs and uncertainty about results may cause a lack of confidence at financial return	[12, 22, 23, 29–32]
	B03	Lack of financing capacity	Budget constraints and lack of funding can limit company investments	[20, 23, 25, 28, 33–35]
	B04	Lack of long-term planning	Lack of immediate results discourages companies focused on short-term profitability	[22, 25, 28, 32]
	B05	Lack of risk acceptance	Traditional organizations usually avoid innovative projects due to the risk	[21, 36, 37]
Management	B06	Lack of knowledge about SCE	As the concept of SCE is not widespread, many companies do not know the opportunities	[20, 23, 25, 28, 33, 37]
	B07	Lack of inclusion of DTs in the processes	Lack of digitalization models and knowledge about DTs can lead to processes poorly adapted to the SCE, especially when it envolves human-machine interaction	[23, 26, 27, 31, 38, 33]
	B08	Lack of innovation in BMs	Due to the lack of creativity and market acceptance, companies find it difficult to redefine the BMs	[23, 27, 28, 33, 39]

(*continued*)

Table 1. (*continued*)

Category	Code	Name	Description	References
	B09	Lack of decentralized decision-making	Hierarchical strucures do not allow decision-making at the operational level, which is necessary in the SCE	[12, 23, 35]
	B10	Lack of leadership	Companies do not find experienced and engaged leaders because the concept of SCE is new	[23, 28, 35]
Infrastructure	B11	Lack of skilled labor	Due to the lack of knowledge about SCE and the high training costs, organizations lack specialized labor	[12, 20–22, 29, 34–37]
	B12	Lack of adequate IT infrastructure	Insisting on using old IT infrastructure can lead to implementation and operation problems	[12, 23, 26, 27, 35, 37]
Network	B13	Lack of collaboration between partners	Stakeholder competition and lack of coordination may cause poor integration across the product lifecycle	[20, 24, 25, 28–30, 33, 35, 37, 38, 40]
	B14	Lack of customer sustainable behavior	Lack of sustainability culture can lead to a lack of sustainable behaviors such as seeking maintenance or separating recyclable waste	[28–31, 36, 37, 39, 41, 42]
	B15	Lack of governmental control	Outdated laws and unstructured state policies do not stimulate sustainability and digitalization, and even discourage through excessive taxation	[20, 22, 24, 28, 35–37, 42, 43]

(*continued*)

Table 1. (*continued*)

Category	Code	Name	Description	References
	B16	Lack of data sharing skills	Data sharing is hampered by issues such as information sensitivity, intellectual property, lack of data integrity, and lack of standards for data interoperability	[27, 30, 33, 37, 40, 42–45]
	B17	Lack of partners	Lack of suppliers and means of accessing other actors in the supply chain can limit SCE implementation	[29, 35, 38, 41]
Technology	B18	Lack of DTs integration	Using multiple technologies and lack of standardization make the DTs' interoperability difficult	[21, 23, 24, 26–29, 32, 40]
	B19	Lack of security	Cyber attacks can damage hardware and software, and even make the company vulnerable to blackmailers	[24, 30, 32, 42, 45–47]
	B20	Lack of data collection skills	Lack of experience and skilled labor may cause several difficulties on data collection, such as inappropriate models and data loss	[8, 21, 31, 34, 40, 41]
	B21	Lack of privacy	In some applications, it is impossible to guarantee that users are not identifiable. In addition, cyber attacks may also cause information leakage, compromising user privacy	[8, 24, 30, 46, 47]

(*continued*)

Table 1. (*continued*)

Category	Code	Name	Description	References
	B22	Lack of data analysis skills	Analyzes are usually descriptive, but it is not as useful to support decision-making as prescriptive analysis	[8, 23, 27, 46]
	B23	Lack of storage and processing capacities	Current state of technology development may be insufficient for more demanding applications such as blockchain	[40, 42, 46, 47]
	B24	High frequency of failures	Sensor malfunctions and communication instabilities can occur at high frequencies and make the use of data unfeasible	[21, 34, 37]

The first indication of the model is that companies face financial issues mainly in the early steps of change. As small and medium-sized enterprises are more constrained to invest in innovation, they may find it difficul to start the transition [25]. Secondly, the technological barriers emerge mainly in the advanced steps, "move" and "refreeze". Thus, organizational and strategic aspects of the change may be the most relevant in the current stage of SCE development.

The results also show that the "move" is the most complex step, because companies must deal with problems in all categories. Developing models for this step is a promising research area, because there is a lack of implementation models on CE research [9]. Finally, the "network" category is the only one that influences all change steps. This indicates that stakeholders play a central role in the SCE transition, as discussed in the Subsect. 3.1. The barriers for each step are explained below.

Unfreeze. In the first step of change, the current organization's values and mindset must be reviewed [11]. The resistance to change needs to be overcome [16]. Regarding the transition towards SCE, we identify initial barriers such as lack of long-term planning (B04), risk aversion (B05) and lack of innovation in BMs (B08). Often, the motivation to overcome them comes from external pressures, such as governmental policies (B15).

Move. In the second step, the new mindset should be translated into organizational behaviors and capabilities [11]. It requires resources and a planning for change [16, 18]. Regarding SCE transition, we identify internal barriers such as lack of leadership (B10), lack of human resources (B11) or IT infrastructure (B12), and the need to adapt the processes (B07). As several SCE strategies require integration throughout the product lifecycle, barriers related to find partners (B17) arise in this step.

Categories of barriers	Unfreeze	Move	Refreeze
Technology		B18 - Lack of DTs integration B23 - Lack of storage and processing capacities	B19 - Lack of security B20 - Lack of data collection skills B21 - Lack of privacy B22 - Lack of data analysis skills B24 - High frequency of failures
Network	B15 - Lack of governmental control	B17 - Lack of partners	B13 - Lack of collaboration between partners B14 - Lack of customer sustainable behavior B16 - Lack of data sharing skills
Infra.		B11 - Lack of skilled labor B12 - Lack of adequate IT infrastructure	
Management	B06 - Lack of knowledge about SCE B08 - Lack of innovation in BMs	B07 - Lack of inclusion of DTs in the processes B09 - Lack of decentralized decision-making B10 - Lack of leadership	
Finance	B02 - Lack of confidence in investment B04 - Lack of long-term planning B05 - Lack of risk acceptance	B01 - High initial costs B03 - Lack of financing capacity	
	Three steps of transition		

Fig. 3. Barriers to transitioning towards SCE based on the three-step change model.

Refreeze. In the third step, the change must to be consolidated. The organization must incorpore new norms and practices into its culture to avoid regression in the process [16, 18]. Regarding SCE transition, the challenges are related to the operation of DTs implemented. Pioneering companies report the need to improve skills in data management (B16, B20, and B22), problems related to technical failures (B24), and security issues (B19), among others.

4 Final Remarks

This research contributes to theory and practice of sustainable management by exploring the barriers faced by companies during the transition towards SCE. Through a SLR, we identified the main barriers and separate them into different organizational change steps. The results have implications for public policy, business and academic research.

Our analysis suggests that governments play an important role in stimulating the SCE transition through environmental legislation. However, it can also act on two main issues. First, economic policies can estimulate financing lines for this transformation [20], mainly benefiting small and medium-sized enterprises [25]. Second, educational policies for human resource development can benefit economic development and job creation [20]. These actions may help to overcome barriers B03, B11 and B15.

From the companies' view, aligning digitalization with sustainability is an opportunity for innovation and value creation [48, 49]. To get these advantages, managers must carry out a consistent SCE implementation project, taking into account the current and desired state of the company. Our model can be useful for diagnosing the current state and predicting future challenges. We also recommended that firms should develop strategic partners and humans resources to succeed in the transition.

Finally, we suggest that future academic research should focus on solutions to the most relevant problems. CE BMs analyzed by Pieroni et al. [9] cover aspects such as knowledge about SCE and innovation, related to the barriers B06 and B08. But our analysis implies that solutions are still needed to estimulate stakeholder cooperation. Promising solutions to increase trust between partners are blockchain technology [32, 47] and data marketplaces [44]. These innovations may help to overcome barriers B13 and B17.

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References

1. Kirchherr, J., Reike, D., Hekkert, M.: Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recy. **127**, 221–232 (2017)
2. Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J.: The circular economy – a new sustainability paradigm? J. Clean. Prod. **143**, 757–768 (2017)
3. Ghisellini, P., Cialani, C., Ulgiati, S.: A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. **114**, 11–32 (2016)
4. Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A.: Circular economy: measuring innovation in the product chain. PBL, The Hague, Netherlands (2017)
5. Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., Terzi, S.: Assessing relations between circular economy and industry 4.0: a systematic literature review. Int. J. Prod. Res. **58**(6), 1662–1687 (2020)
6. Kristoffersen, E., Li, Z., Li, J., Jensen, T.H., Pigosso, D.C., McAloone, T.C.: Smart circular economy: CIRCit workbook 4. DTU, Kongens Lyngby, Denmark (2020)
7. Ingemarsdotter, E., Jamsin, E., Kortuem, G., Balkenende, R.: Circular strategies enabled by the internet of things – a framework and analysis of current practice. Sustainability **11**(20), 5689 (2019)
8. Wang, N., Ren, S., Liu, Y., Yang, M., Wang, J., Huisingh, D.: An active preventive maintenance approach of complex equipment based on novel product-service system operation mode. J. Clean. Prod. **277**, 123365 (2020)
9. Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A.: Business model innovation for circular economy and sustainability: a review of approaches. J. Clean. Prod. **215**, 198–216 (2019)
10. Korhonen, J., Honkasalo, A., Seppälä, J.: Circular economy: the concept and its limitations. Ecol. Econ. **143**, 37–46 (2018)

11. Bertassini, A.C., Ometto, A.R., Severengiz, S., Gerolamo, M.C.: Circular economy and sustainability: the role of organizational behaviour in the transition journey. Bus. Strat. Env. 1–34 (2021)
12. Ozkan-Ozen, Y.D., Kazancoglu, Y., Kumar Mangla, S.: Synchronized barriers for circular supply chains in industry 3.5/industry 4.0 transition for sustainable resource management. Resour. Conserv. Recy. **161**, 104986 (2020)
13. Tranfield, D., Denyer, D., Smart, P.: Towards a methodology for developing evidence-informed management knowledge by means of systematic review. Br. J. Manag. **14**, 207–222 (2003)
14. Briner, R.B., Denyer, D.: Systematic review and evidence synthesis as a practice and scholarship tool. In: Rousseau, D.M. (ed.) The Oxford handbook of evidence-based management, pp. 112–129. Oxford University Press, New York, USA (2012)
15. Miles, M.B., Huberman, A.M., Saldaña, J.: Qualitative Data Analysis: A Methods Sourcebook. 3rd ed. SAGE, Thousand Oaks, USA (2014)
16. Lewin, K.: Frontiers in group dynamics: concept, method and reality in social science; social equilibria and social change. Hum. Relat. **1**(1), 5–41 (1947)
17. Elrod, P.D., Tippett, D.D.: The "death valley" of change. JOCM **15**(3), 273–291 (2002)
18. Burnes, B.: The origins of Lewin's three-step model of change. JABS **56**(1), 32–59 (2020)
19. Konietzko, J., Bocken, N., Hultik, E.J.: Circular ecosystem innovation: an initial set of principles. J. Clean. Prod. **253**, 119942 (2020)
20. Cezarino, L.O., Liboni, L.B., Oliveira Stefanelli, N., Oliveira, B.G., Stocco, L.C.: Diving into emerging economies bottleneck: Industry 4.0 and implications for circular economy. Manag. Decis. (2019)
21. Kerin, M., Pham, D.T.: Smart remanufacturing: a review and research framework. J. Manuf. Technol. Manag. **31**(6), 1205–1235 (2020)
22. Kumar, P., Singh, R.K., Kumar, V.: Managing supply chains for sustainable operations in the era of industry 4.0 and circular economy: analysis of barriers. Resour. Conserv. Recy. **164**, 105215 (2021)
23. Abdul-Hamid, A.-Q., Ali, M.H., Tseng, M.-L., Lan, S., Kumar, M.: Impeding challenges on industry 4.0 in circular economy: palm oil industry in Malaysia. Comput. Oper. Res. **123**, 105052 (2020)
24. Hatzivasilis, G., Soultatos, O., Ioannidis, S., Verikoukis, C., Demetriou, G., Tsatsoulis, C.: Review of security and privacy for the internet of medical things (IoMT): resolving the protection concerns for the novel circular economy bioinformatics. In: Proceedings of DCOSS 2019. IEEE, Santorini, Greece, pp. 457–464 (2019)
25. Kumar, R., Singh, R.K., Dwivedi, Y.K.: Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: analysis of challenges. J. Clean. Prod. **275**, 124063 (2020)
26. Rajput, S., Singh, S.P.: Connecting circular economy and industry 4.0. IJIM **49**, 98–113 (2019)
27. Rajput, S., Singh, S.P.: Industry 4.0 – Challenges to implement circular economy. Benchmarking (2019)
28. Zhang, A., Venkatesh, V.G., Liu, Y., Wan, M., Qu, T., Huisingh, D.: Barriers to smart waste management for a circular economy in China. J. Clean. Prod. **240**, 118198 (2019)
29. Chiappetta Jabbour, C.J., et al.: First-mover firms in the transition towards the sharing economy in metallic natural resource-intensive industries: Implications for the circular economy and emerging industry 4.0 technologies. Resour. Policy **66**, 101596 (2020)
30. Esmaeilian, B., Wang, B., Lewis, K., Duarte, F., Ratti, C., Behdad, S.: The future of waste management in smart and sustainable cities: a review and concept paper. Waste Manage. **81**, 177–195 (2018)
31. Ingemarsdotter, E., Jasmin, E., Balkenende, R.: Opportunities and challenges in IoT-enabled circular business model implementation – a case study. Resour. Conserv. Recy. **162**, 105047 (2020)

32. Kouhizadeh, M., Zhu, Q., Sarkis, J.: Blockchain and the circular economy: potential tensions and critical reflections from practice. Prod. Plan. Control **31**(11–12), 950–966 (2020)
33. Antikainen, M., Uusitalo, T., Kiviikytö-Reponen, P.: Digitalisation as an enabler of circular economy. Proc. CIRP **73**, 45–49 (2018)
34. Fisher, O.J., et al.: Considerations, challenges and opportunities when developing data-driven models for process manufacturing systems. Comput. Chem. Eng. **140**, 106881 (2020)
35. Prendeville, S., Hartung, G., Purvis, E., Brass, C., Hall, A.: Makespaces: From redistributed manufacturing to a circular economy. In: Setchi, R., Howlett, R.J., Liu, Y., Theobald, P. (eds.) SDM 2016, SIST, vol. 52, pp. 577–588. Springer, Cham, Switzerland (2016)
36. Chauhan, C., Sharma, A., Singh, A.: A SAP-LAP linkages framework for integrating industry 4.0 and circular economy. Benchmarking (2019)
37. Väisänen, J.-M., Ranta, V., Aarikka-Stenroos, L.: Enabling Circular Economy with Software: A Multi-level Approach to Benefits, Requirements and Barriers. In: Hyrynsalmi, S., Suoranta, M., Nguyen-Duc, A., Tyrväinen, P., Abrahamsson, P. (eds.) ICSOB 2019. LNBIP, vol. 370, pp. 252–259. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-33742-1_20
38. Tolio, T., et al.: Design, management and control of demanufacturing and remanufacturing systems. CIRP Ann. Manuf. Techn. **66**(2), 585–609 (2017)
39. Dominish, E., et al.: "Slowing" and "narrowing" the flow of metals for consumer goods: evaluating opportunities and barriers. Sustainability **10**, 1096 (2018)
40. Bressanelli, G., Perona, M., Saccani, N.: Towards the circular supply chain: a literature review of challenges. In: Proceedings of 23th Summer School Francesco Turco. AIDI, Palermo, Italy, pp. 171–178 (2018)
41. Kerdlap, P., Low, J.S.C., Ramakrishna, S.: Zero waste manufacturing: a framework and review of technology, research, and implementation barriers for enabling a circular economy transition in Singapore. Resour. Conserv. Recy. **151**, 104438 (2019)
42. Chiappetta Jabbour, C.J., Fiorini, P.D.C., Ndubisi, N.O., Queiroz, M.M., Piato, É.L.: Digitally-enabled sustainable supply chains in the 21st century: a review and a research agenda. Sci. Total Environ. **725**, 138177 (2020)
43. Pyakurel, P., Wright, L.: Energy and resources cooperation for greenhouse gases emissions reduction of industrial sector. E&E (2020)
44. Blömeke, S., et al.: Recycling 4.0: an integrated approach towards an advanced circular economy. In: Proceedings of ICT4S 2020. ACM, New York, USA, pp. 66–76 (2020)
45. Jensen, J.P., Remmen, A.: Enabling circular economy through product stewardship. Proc. Manuf. **8**, 377–384 (2017)
46. Andrade, R.O., Yoo, S.G.: A comprehensive study of the use of LoRa in the development of smart cities. Appl. Sci. **9**, 4753 (2019)
47. Damianou, A., Angelopoulos, C.M., Katos, V.: An architecture for blockchain over edge-enabled IoT for smart circular cities. In: Proceedings of DCOSS 2019. IEEE, Santorini, Greece, pp. 465–472 (2019)
48. Ellen MacArthur Foundation: Intelligent assets: unlocking the circular economy potential. Report (2016)
49. Ellen MacArthur Foundation: Artificial intelligence and the circular economy: AI as a tool to accelerate the transition. Report (2019)

Fault Diagnosis in Industries: How to Improve the Health Assessment of Rotating Machinery

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Abstract. Rotating machinery like pumps, compressors, and engines, are widespread in industries. A failure in one or more of their components, e.g., rolling bearings and gearboxes, may cause system breakdowns or even catastrophic events. Hence, fault diagnosis of rotating machinery is achieving great attention from both the industrial and academic fields. After collecting signals from sensors mounted on different locations, different condition monitoring techniques, e.g., vibration analysis and acoustic emissions, are usually applied to get accurate information on machinery health conditions. The most challenging step in the fault diagnosis process is feature extraction from collected signals, which describe the fault behavior synthetically while retaining as much information as possible. In intelligent fault diagnosis, the extracted features feed Machine Learning algorithms for fault classification. However, given the high number of variables that result from feature extraction, dimensionality reduction should be performed to improve the classification accuracy and training times of intelligent methods. In the literature, the problem of dimensionality reduction is faced through feature selection and feature fusion. These methods are often combined in different ways, resulting in a broad range of possible solutions. In this paper, a bibliometric analysis is conducted to discover trends over time and identify the connections between the different activities of the fault diagnosis process using dimensionality reduction techniques. The present study's main result lies in identifying the most promising frameworks for industrial applications of fault diagnosis using dimensionality reduction.

Keywords: Fault diagnosis · Rotating machinery · Dimensionality reduction · Feature selection · Feature fusion

1 Introduction

Rotating machinery is very common in industries, and its failure may cause system breakdowns or even catastrophic accidents [1]. Fault diagnosis aims to monitor the health condition of components and detect the occurrence of a failure. Among fault diagnosis techniques, such as vibration-based, current-based, and acoustic emission-based, the vibration-based diagnostic is the most adopted, as vibration signals can describe the

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dynamic behavior of rotating machinery [2]. Given the increasing complexity of systems, physics-based models often fail to describe the system behavior, especially under varying operating conditions. Therefore, data-driven methods based on Machine Learning (ML) are increasingly adopted for vibration-based fault diagnosis of rotating machinery.

The process of fault diagnosis of rotating machinery using a data-driven approach consists of two main steps. First, it is necessary to process and transform raw signals to extract useful fault information [3]. Then, faults are identified using classification models using the extracted information. The most challenging step is the first one, which basically includes signal processing techniques and feature extraction methods. Signal processing consists of processing raw signals in the time, frequency, or time-frequency domain to extract features [4]. Features can be defined as parameters derived from the measured signals that robustly indicate the presence of rotating machinery faults [5]. These features should have two main properties. First, they should be relevant to reveal the health condition of the system; second, they should be non-redundant to reduce the computational complexity and training times of ML algorithms used for fault diagnostic. However, both signal processing and feature extraction increase the number of variables, i.e., the features of the dataset. Therefore, it is necessary to identify a smaller feature set that best represents the system's health condition [6].

In the context of data science, the task of reducing the number of variables in a dataset is referred to as Dimensionality Reduction (DR) [7]. It can be performed by feature selection or feature fusion methods. In the first case, the dimension of the dataset is reduced by selecting the subset of features that most contribute to the classification accuracy and eliminating those that contain redundant information. In the second case, original features are subject to different kinds of transformation to produce features with more informative content [8].

In the context of fault diagnosis, the distinction among different dimensionality reduction methods is not always clear. In particular, feature extraction is often used for signal processing, feature learning, and feature fusion.

This paper aims to provide a systematic classification of the existing literature on dimensionality reduction methods adopted in fault diagnosis of rotating machinery. To this purpose, a bibliometric analysis is first conducted to identify the publishing trend and relevant topics. Then, a co-occurrence analysis is conducted on the author keywords in order to identify the activities conducted for dimensionality reduction and their connections. Finally, a systematic classification of existing frameworks is proposed. The Scopus database is used to collect the documents and perform trend and citation analyses, while the freely available software VOS viewer is used to construct the bibliometric map and perform the co-occurrence analysis [9].

The remainder of this paper is organized as follows. Section 2 is dedicated to the description of the state-of-the-art (publishing trend and identification of most relevant papers) on dimensionality reduction for intelligent fault diagnosis of rotating machinery. In addition, the connections between activities conducted for dimensionality reduction that emerged from the co-occurrence analysis are described. Section 3 is dedicated to the description of the identified frameworks and the classification of existing papers into the identified frameworks. Finally, the main results and conclusions are presented in Sect. 4.

2 Bibliometric Analysis

This section describes the bibliometric analysis of papers related to dimensionality reduction techniques for fault diagnosis of rotating machinery. The papers are collected from the Scopus database through the following search query:

$$\left(\begin{array}{c} diagnos^{*} ORfaultidentificationORfaultdetection \\ ORprognos^{*} healthmanagement \\ AND \\ feature^{*} extractionORfeature^{*} selectionORfeature^{*} learningOR \\ feature^{*} fusionORfeature^{*} constructionORfeature^{*} engineeringOR \\ dimension^{*} reduction \\ AND \\ rotat^{*} machin^{*} \end{array}\right) \qquad (1)$$

In total, after the elimination of non-English papers, 1639 documents were found. The publishing trend over time is shown in Fig. 1. Unlike results obtained in [10], in which a bibliometric analysis on fault diagnosis of rotating machinery was conducted, the number of published papers starts to increase after 2003, showing a delay of 6 six years regarding the more general topic of fault diagnosis. Since then, an increasing number of papers have been published. In particular, 2017 and 2019 are the year with the maximum increase with respect to the previous year.

Among the 1639 documents, only 5 reviews are present. However, they have mainly focused on signal processing techniques rather than dimensionality reduction techniques. In particular, time-frequency domain analysis methods and AI methods [2], entropy theories [1], and cyclostationary analysis [11] are reviewed for early fault diagnosis of rotating machinery.

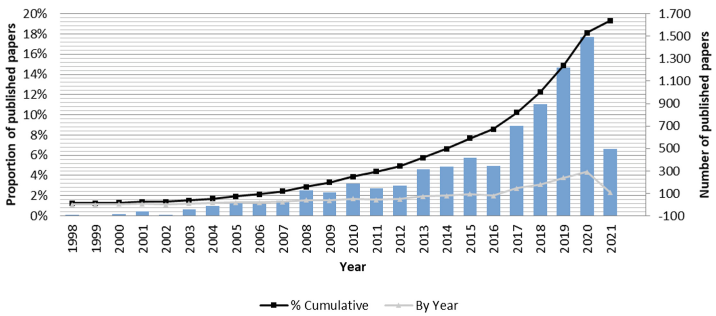

Fig. 1. Publishing trend

Citation analysis has been conducted to analyze the most influential papers in this context. Table 1 shows the 10 most cited papers with the corresponding Journal.

In all these works, the importance of dimensionality reduction for fault diagnosis is highlighted. With time, the focus moved from the use of signal processing and feature extraction methods towards feature selection after feature extraction first and the

Table 1. The top 10 cited articles.

No	Article	Journal	Number of citations
1	Jia et al. (2016) [12]	Mechanical Systems and Signal Processing	841
2	Samanta et al. (2003) [13]	Mechanical Systems and Signal Processing	553
3	Lu et al. (2017) [14]	Signal Processing	366
4	Bin et al. (2012) [5]	Mechanical Systems and Signal Processing	351
5	Chen et al. (2017) [15]	IEEE Transactions on Instrumentation and Measurement	323
6	Hu et al. (2007) [16]	Mechanical Systems and Signal Processing	319
7	Sugumaran et al. (2007) [17]	Mechanical Systems and Signal Processing	308
8	Lei et al. (2007) [18]	Mechanical Systems and Signal Processing	301
9	Lei et al. (2008) [19]	Expert Systems with Applications	289
10	Shao et al. (2017) [20]	Mechanical Systems and Signal Processing	257

use of unsupervised feature learning then. The first two papers in Table 1 represent a very breakthrough in the literature, applying for the first time in the context of fault diagnosis feature extraction and deep learning. In 2003, an intelligent fault diagnosis method for rolling bearings based on signal processing techniques and time-domain feature extraction had been proposed to improve training time and accuracy of ANNs for fault classification [13]. In 2007, feature selection methods were applied after feature extraction [16–19]. In 2012, Bin et al. proposed a novel energy feature that allows selecting the most appropriate processed signal for further feature extraction [5]. Finally, in 2016 and 2017, deep neural networks are proposed with the primary goal of avoiding the time-consuming and labor-intensive activity of manual feature extraction [12, 14, 15, 20]. Indeed, in contrast to shallow structures, deep structures can automatically learn discriminative features in an automatic and unsupervised manner.

In these works, five main activities can be distinguished: signal processing, feature extraction, feature selection, feature fusion, and feature learning. A co-occurrence analysis on the paper keywords is conducted to identify groups of activity, tools, and methods usually performed. In Fig. 2, the resulting graph obtained with the software VOSviewer is shown, where the size of circles is proportional to the number of occurrences of a keyword.

Because only keywords with a minimum number of occurrences equal to 6 are visualized in the graph, 126 keywords are shown in the graph. In addition, the keywords fault diagnosis and rotating machinery are not visualized because they are linked to all other

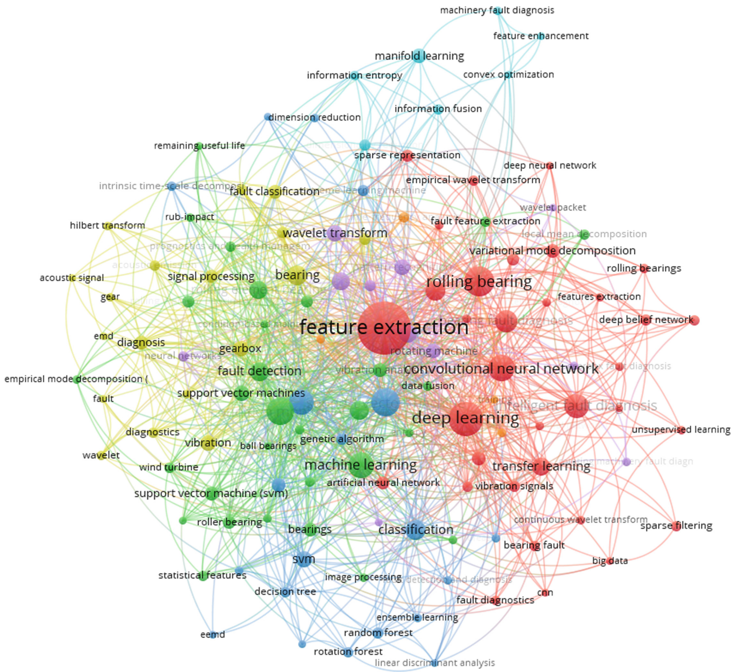

Fig. 2. Keyword-based co-occurrence analysis

keywords. From Fig. 2, it can be seen that the most occurred keyword is feature extraction, which demonstrates the importance of this task in the intelligent fault diagnosis process. In particular, feature extraction has been used in 218 papers and has often been used together with feature selection, signal processing, dimensionality reduction, and information fusion. Feature selection occurred 54 times and is connected with feature extraction, signal processing, and dimensionality reduction. Signal processing has been used in 16 papers and is linked with feature extraction and feature selection. Dimensionality reduction occurred 20 times and is connected with feature extraction, feature selection, and information fusion. Finally, a separated group is represented by feature learning, which occurred only 11 times and is not connected with any of the other tasks.

To better understand how dimensionality reduction is usually performed, only papers using the keywords corresponding to the tasks identified in the most cited papers are analyzed. In addition, because of the high number of papers that face these topics, only the last three years (from 2019 to 2021) are considered to identify existing frameworks.

A deep investigation of the collected papers allowed to draw the following considerations. First, the reduction of the number of variables is classified as a dimensionality reduction technique in few cases only. Therefore, if papers are searched by using only the keyword dimensionality reduction in the search query, many documents implementing such a task do not appear. In addition, dimensionality reduction is also associated with traditional feature extraction and signal processing, which are often used indistinctly to extract statistical features in the time, frequency, and time-frequency domains. However, in this sense, they cannot be considered dimensionality reduction techniques. Second, the number of papers using the keyword feature learning is minimal. This is because feature extraction or deep learning refers to the automatic and unsupervised learning of high-level features. However, feature extraction and feature learning are very different from each other. In the first case, the statistical features to extract are set by the user. In the second case, at each layer of the deep architecture, a certain transformation is realized. However, no human intervention is required. In addition, deep learning is a tool; thus it is also used for other purposes, e.g., diagnostics and prognostics. This results in the impossibility of identifying when they are actually used for feature learning or diagnostics and prognostics. Finally, the use of feature fusion is limited. Very often, information fusion and sensor data fusion are used instead of feature fusion. However, they refer to the fusion of multiple signals collected through different sensors and not the combination of previously extracted features. In addition, feature extraction is also used when multiple features are combined to provide more accurate and robust features.

The variability in the terminology causes great confusion when approaching the dimensionality reduction problem for fault diagnosis. For this reason, a systematic classification of existing frameworks and approaches for dimensionality reduction is needed.

3 Systematic Classification of Existing Approaches

The proposed classification of the connections held between the activities conducted for dimensionality reduction is shown in Fig. 3. Basically, dimensionality reduction for fault diagnosis of rotating machinery is realized through two activities: feature selection and feature fusion, which are almost always applied after signal processing, feature extraction, or feature learning. Signal processing includes all those activities for noise removal or signal transformation into frequency and time-frequency domains. After signal processing, feature extraction or feature learning can be performed. In the first case, statistical features are extracted from raw or processed signals. It cannot be considered a dimensionality reduction technique as it reduces the number of samples while increasing the number of variables of the dataset. In the second case, features are automatically learned from raw or processed data. Thus, feature learning is an alternative way to automatically learn the optimal data representation from raw or processed signals [21, 22]. If the number of features manually extracted or/and automatically learned is too high, feature selection or feature fusion are conducted before fault classification, which effectively corresponds to two distinct ways to perform dimensionality reduction.

In Table 2, examples of papers implementing the identified approaches are summarized. In [23], signals are first transformed into the frequency domain by means of a signal processing technique before the extraction of statistical features. Then, the most sensitive features are selected through the Relief algorithm. A similar approach using different techniques for signal processing, feature extraction, and feature selection can be found in [24–26]. In [27], only feature extraction and selection are performed. Hence, statistical features are extracted directly from raw signals without a previous signal processing technique; then, a Genetic Algorithm is used for feature selection.

Similarly, in [28], features are first extracted from raw signals. Then, feature selection is performed in three steps: a classification model, a correlation analysis, and the

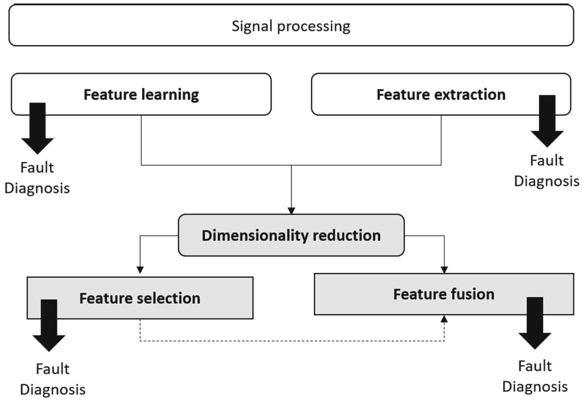

Fig. 3. Classification of activities and approaches

Principal Component Analysis (PCA). PCA is usually considered a feature extraction method. However, in this work, the obtained Principal Components are weighted and fused to obtain the score ranking of the original features. Hence, since the resulting feature set is made of original features, it is more appropriate to consider the PCA adopted in this work as a feature selection method. In [29], the PCA method has been used as a feature fusion method after signal processing and feature extraction. In [30], a Genetic Programming (GP) made of 7 layers is applied for signal processing, feature extraction, feature construction, and feature combination. The last two layers correspond to a two-step feature fusion. In [31], both feature extraction and feature learning are applied in parallel before feature selection. In particular, two signal processing techniques are applied before feature extraction. The first technique generates signals that are used to learn the features through a deep neural network. The other technique is applied to extract a second set of features, consisting of statistical features extracted from processed signals in the time and frequency domains. Finally, the distance-based feature selection method is applied to both feature sets to select the sensitive features that will be used for fault diagnosis. Hence, four different frameworks are identified, which include: signal processing, feature extraction, and feature selection; feature extraction and feature selection; signal processing, feature extraction, and feature fusion; signal processing, feature extraction and feature learning (in parallel), and feature selection.

Table 2. Adopted approaches.

Ref.	Signal processing	Feature extraction	Feature learning	Feature selection	Feature fusion
[23–26]	X	X		X	
[27, 28]		X		X	
[29, 30]	X	X			X
[31]	X	X	X	X	

4 Conclusions

In this paper, the problem of dimensionality reduction for fault diagnosis of rotating machinery is investigated. In particular, a bibliometric analysis is conducted to discover publishing trends and typical activities involved in the fault diagnosis process. Results show that, from 2003, an increasing number of papers related to this topic have been published. In particular, a breakthrough is represented by deep learning models, which have been investigated since 2016 for automatic feature learning. These models allow avoiding the time-consuming and knowledge-based feature extraction. However, deep learning has numerous drawbacks from the industrial point of view, including the need for a large amount of high-quality data that is difficult to collect for industries [10]. Therefore, many studies are conducted on traditional dimensionality reduction techniques, like feature selection and feature fusion, which allow identifying relevant features for training the models that provide the best fault classification accuracy. Given the low computational time required by these methods, the so-identified features can be extracted in streaming for future inference, enabling the real-time fault diagnosis of rotating machinery [32]. A co-occurrence analysis based on author keywords has also been conducted in this study to identify typical frameworks for intelligent fault diagnosis of rotating machinery using dimensionality reduction techniques. It resulted that only feature selection and feature fusion can be considered dimensionality reduction techniques and that they can be included in four different frameworks. After signal collection, signals may be processed in one of the analysis domains; then, statistical features can be extracted from raw signals and processed signals; finally, relevant features can be selected or constructed by feature selection or feature fusion techniques, respectively. Features can also be selected or fused using features obtained from feature extraction and feature learning.

A systematic classification of existing literature on dimensionality reduction into four different frameworks has been conducted in this study. However, typical models for the realization of this task are not reviewed. Therefore, a comprehensive literature review of such methods will be the object of future studies.

References

1. Liu, L., Zhi, Z., Zhang, H., Guo, Q., Peng, Y., Liu, D.: Related entropy theories application in condition monitoring of rotating machineries. Entropy **21**, 1061 (2019)
2. Wei, Y., Li, Y., Xu, M., Huang, W.: A review of early fault diagnosis approaches and their applications in rotating machinery. Entropy **21**, 409 (2019)
3. Sarih, H., Tchangani, A.P., Medjaher, K., Pere, E.: Data preparation and preprocessing for broadcast systems monitoring in PHM framework. In: 2019 6th Int. Conf. Control. Decis. Inf. Technol. CoDIT 2019, no. Cm, pp. 1444–1449 (2019)
4. Jardine, A.K.S., Lin, D., Banjevic, D.: A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech. Syst. Signal Process. **20**(7), 1483–1510 (2006)
5. Bin, G.F., Gao, J.J., Li, X.J., Dhillon, B.S.: Early fault diagnosis of rotating machinery based on wavelet packets — empirical mode decomposition feature extraction and neural network. Mech. Syst. Signal Process. **27**(1), 696–711 (2012)

6. Calabrese, F., Regattieri, A., Botti, L., Mora, C., Galizia, F.G.: Unsupervised fault detection and prediction of remaining useful life for online prognostic health management of mechanical systems. Appl. Sci. **10**(12), 4120 (2020)
7. Calabrese, F., Regattieri, A., Bortolini, M., Gamberi, M., Pilati, F.: Predictive maintenance: a novel framework for a data-driven, semi-supervised, and partially online prognostic health management application in industries. Appl. Sci. **11**, 1–28 (2021)
8. Tang, J., Alelyani, S., Liu, H.: Feature selection for classification: a review. In: Aggarwal, C.C. (ed.) Data Classification Algorithms and Applications, 1st ed., New York, pp. 2–28 (2014)
9. Van Eck, N.J., Waltman, L.: Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics **84**(2), 523–538 (2010)
10. Chen, J., Lin, C., Peng, D., Ge, H.: Fault diagnosis of rotating machinery: a review and bibliometric analysis. IEEE Access **8**, 224985–225003 (2020)
11. Tang, S., Yuan, S., Zhu, Y.: Cyclostationary analysis towards fault diagnosis of rotating machinery. Processes **8**(10), 1–15 (2020)
12. Jia, F., Lei, Y., Lin, J., Zhou, X., Lu, N.: Deep neural networks: a promising tool for fault characteristic mining and intelligent diagnosis of rotating machinery with massive data. Mech. Syst. Signal Process. **72–73**, 303–315 (2016)
13. Samanta, B., Al-Balushi, K.R.: Artificial neural network based fault diagnostics of rolling element bearings using time-domain features. Mech. Syst. Signal Process. **17**(2), 317–328 (2003)
14. Lu, C., Wang, Z.Y., Qin, W.L., Ma, J.: Fault diagnosis of rotary machinery components using a stacked denoising autoencoder-based health state identification. Signal Process. **130**, 377–388 (2017)
15. Chen, Z., Li, W.: Multisensor feature fusion for bearing fault diagnosis using sparse autoencoder and deep belief network. IEEE Trans. Instrum. Meas. **66**(7), 1693–1702 (2017)
16. Hu, Q., He, Z., Zhang, Z., Zi, Y.: Fault diagnosis of rotating machinery based on improved wavelet package transform and SVMs ensemble. Mech. Syst. Signal Process. **21**(2), 688–705 (2007)
17. Sugumaran, V., Muralidharan, V., Ramachandran, K.I.: Feature selection using decision tree and classification through proximal support vector machine for fault diagnostics of roller bearing. Mech. Syst. Signal Process **21**(2), 930–942 (2007)
18. Lei, Y., He, Z., Zi, Y., Hu, Q.: Fault diagnosis of rotating machinery based on multiple ANFIS combination with GAs. Mech. Syst. Signal Process **21**(5), 2280–2294 (2007)
19. Lei, Y., He, Z., Zi, Y.: A new approach to intelligent fault diagnosis of rotating machinery. Expert Syst. Appl. **35**(4), 1593–1600 (2008)
20. Shao, H., Jiang, H., Zhao, H., Wang, F.: A novel deep autoencoder feature learning method for rotating machinery fault diagnosis. Mech. Syst. Signal Process. **95**, 187–204 (2017)
21. Deng, F., Ding, H., Yang, S., Hao, R.: An improved deep residual network with multiscale feature fusion for rotating machinery fault diagnosis. Meas. Sci. Technol. **32**(2), 2020
22. Li, H., Huang, J., Ji, S.: Bearing fault diagnosis with a feature fusion method based on an ensemble convolutional neural network and deep neural network. Sensors (Switzerland) **19**(9), (2019)
23. Alzghoul, A., Jarndal, A., Alsyouf, I., Bingamil, A.A., Ali, M.A., AlBaiti, S.: On the usefulness of pre-processing methods in rotating machines faults classification using artificial neural network. J. Appl. Comput. Mech. **7**(1), 254–261 (2021)
24. Rohan, A., Raouf, I., Kim, H.S.: Rotate vector (Rv) reducer fault detection and diagnosis system: towards component level prognostics and health management (phm). Sensors (Switzerland) **20**(23), 1–31 (2020)
25. Patel, S.P., Upadhyay, S.H.: Euclidean distance based feature ranking and subset selection for bearing fault diagnosis. Expert Syst. Appl. **154** (2020)

26. Pan, L., Zhao, L., Song, A., She, S., Wang, S.: Research on gear fault diagnosis based on feature fusion optimization and improved two hidden layer extreme learning machine. Meas. J. Int. Meas. Confed. **177**, 109317 (2021)
27. Toma, R.M., Prosvirin, A.E., Kim, J.M.: Bearing fault diagnosis of induction motors using a genetic algorithm and machine learning classifiers. Sensors (Switzerland) **20**(7) (2020)
28. Li, Y., Dai, W., Zhang, W.: Bearing fault feature selection method based on weighted multidimensional feature fusion. IEEE Access **8**, 19008–19025 (2020)
29. Yunusa-Kaltungo, A., Cao, R.: Towards developing an automated faults characterisation framework for rotating machines. Part 1: Rotor-related faults. Energies **13**, 1394 (2020)
30. Peng, B., Wan, S., Bi, Y., Xue, B., Zhang, M.: Automatic feature extraction and construction using genetic programming for rotating machinery fault diagnosis. IEEE Trans. Cybern. 1–15 (2020)
31. Han, D., Liang, K., Shi, P.: Intelligent fault diagnosis of rotating machinery based on deep learning with feature selection. J. Low Freq. Noise Vib. Act. Control **39**(4), 939–953 (2020)
32. Calabrese, F., Regattieri, A., Botti, L., Galizia, F.G.: Prognostic health management of production systems. New proposed approach and experimental evidences. Procedia Manuf. **39**, 260–269 (2019)

Designing a Research Tool for Sustainable Aquaculture Project

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Abstract. Many research projects require strong interactions between academics and practitioners. Academics often face the challenges of collecting sufficient, high-quality research data, while achieving the project aim and producing practical impact to industrial partners. This paper presents the design of a research tool for data collection that increases industrial engagement in a sustainable aquaculture project. The project aim was to explore digital solutions for improving sustainability of shrimp aquaculture industry in Indonesia. To better facilitate the data collection and industrial engagement, we adapt the life cycle thinking and multi-stakeholder concepts from an existing tool, known as Sustainable Value Analysis Tool, redesign the rationale, and develop a new research tool to meet the specific purposes of this project. The research tool is composed of three parts: mapping and clustering challenges, assessing challenges, and co-designing digital solutions. The research tool was used in a workshop with 12 industrial partners from various organizations across the aquaculture supply chains in Indonesia in August 2019. The findings show that the empirical data collected through this tool is richer and more comprehensive compared to semi-structured interviews, and that the use of the tool greatly improved the industrial engagement. The feedback from the industrial partners shows that the tool has effectively helped them engage in the research process and improved the communication between themselves. This paper therefore suggests that designing and using such research tools is an effective way for data collection and industrial engagement.

Keywords: Research tool · Sustainable aquaculture · Sustainable value analysis tool · Digital solutions

1 Introduction

Many research projects require strong interactions between academics and practitioners. However, academics often face the challenges of collecting sufficient, high-quality

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research data, while achieving the project aim and producing practical impact to industrial partners. To better facilitate research data collection and industrial engagement, this paper presents the design of a research tool for a research project on sustainable shrimp aquaculture. This research tool adapts the key concepts and techniques from an existing tool, known as Sustainable Value Analysis Tool (SVAT) [1, 2], and redesigns the rationale to meet the specific purpose of this research project.

The SVAT was initially developed to help firms discover opportunities to create and capture sustainable value across the product life cycle [1]. It provides a structured approach for firms to analyze the value uncaptured [3] for key stakeholders across the entire product life cycle, and identify new opportunities for sustainable value creation. The tool has been effective in assisting firms in innovating their business models for sustainability and identifying new value opportunities for circular economy [2, 4, 5]. It has been used for consultancy, business training and university education in sustainable business model innovation. Later, the concepts of SVAT were embedded into roadmapping process [7, 8], and a new tool, i.e., Sustainable Value Roadmapping Tool (SVRT) [6], was developed to help managers develop sustainable business visions and build strategic pathway towards them. The tool has been used for sustainable strategic planning of adopting additive manufacturing in short-, medium- and long-term [9]. The SVAT has also been used in the combination with other tools to design new business models, such as Business Model Canvas [10], Value Mapping Tool [5, 11], and Sustainable Value Proposition Builder [12]. So far, the SVAT has been mostly used in manufacturing sectors and at firm level, and it is particularly effective to manufacturers transforming towards service-oriented business models, or towards circular economy through end-of-life value analysis.

In this paper, we explore how to design a research tool from SVAT and present a case of using it in a non-manufacturing sector (i.e., aquaculture) and at industry level. The paper will present the key concepts and the application of the SVAT, the design of the research tool and its application in a sustainable shrimp aquaculture project. The results show that the key concepts behind the SVAT can be adjusted flexibly for studying sustainability/circular economy research; and that the empirical data collected through this way seem to be richer and more comprehensive compared to semi-structured interviews. It has also effectively helped the industrial partners to engage in the research process and co-design the practical solutions together with the academics.

2 Sustainable Value Analysis Tool (SVAT)

2.1 Key Concepts

SVAT is built upon four key concepts: life cycle thinking, stakeholder, sustainable value, and multiple forms of value. It provides firms with a scheme to systematically map the stakeholders at each stage of product life cycle, look for value uncaptured, and with a method to design new opportunities [1, 2].

- Life cycle thinking. Product life cycle describes the life of a product from its design to production, usage and finally disposal. A product life cycle is normally divided into beginning of life (BOL), middle of life (MOL), and end of life (EOL). BOL is when product is designed and manufactured; MOL is when product leaves factories and is distributed and used; and EOL is when product is recycled, reused, remanufactured and disposed [13].

- Stakeholders. Stakeholders refer to the "groups and individuals who can affect or be affected" by the actions connected to value creation [14]. There are various stakeholders across the entire product life cycle. Companies need to consider the value creation for all these stakeholders rather than shareholders alone [15, 16].
- Sustainable value. Sustainable value include the value of all three dimensions of sustainability [17], i.e. economic, environmental and social value [18].
- Multiple forms of value. SVAT uses value uncaptured, i.e. the potential value that has not been captured, as a new perspective for business model innovation [3]. It follows a structured approach to identify four forms of value uncaptured, i.e., value surplus, value absence, value destroyed and value missed [2].

2.2 Application of SVAT

The SVAT (Fig. 1a) is composed of a poster and a set of cards with step-by-step guidance. The tool has been used by industrial practitioners from over 100 firms and the feedback has shown that the tool is effective in innovating their business models for sustainability and identifying new value opportunities for circular economy. In most cases, the SVAT was used for purposes related to 1) circular economy, 2) sustainability innovation, 3) business model innovation, and 4) product design and innovation.

To further explore the use case of the tool, Yang and Despeisse [6] developed a Sustainable Value Roadmapping Tool (Fig. 1b) to embed the sustainable value analysis into roadmapping process [7]. It combines the strengths of SVAT and Roadmapping, which has shown to be an effective approach to support managers to integrate sustainability into vision development and strategic planning process. Despeisse et al. [9] further adapted it to help companies build sustainable visions and strategically develop a pathway of adopting additive manufacturing technologies towards the visions.

The SVAT has also been used in combination with other tools for sustainable business model innovation (see Fig. 1c). The Business Model Canvas [10] has been widely utilized to analyze the nine blocks of business models, including the value propositions, customer segment, customer relationships, channels, key partners, key activities, key resources, cost structure and revenue. The Cambridge Value Mapping Tool (CVMT) has been used to map the failed value exchanges (i.e., value missed and destroyed) among different stakeholders and identify the new value opportunities. The Sustainable Value Proposition Builder [12] has been created to help companies develop sustainable value proposition based on new value opportunities, and we found that it is particular effective when these opportunities were resulted from the value analysis supported by CVMT and SVAT.

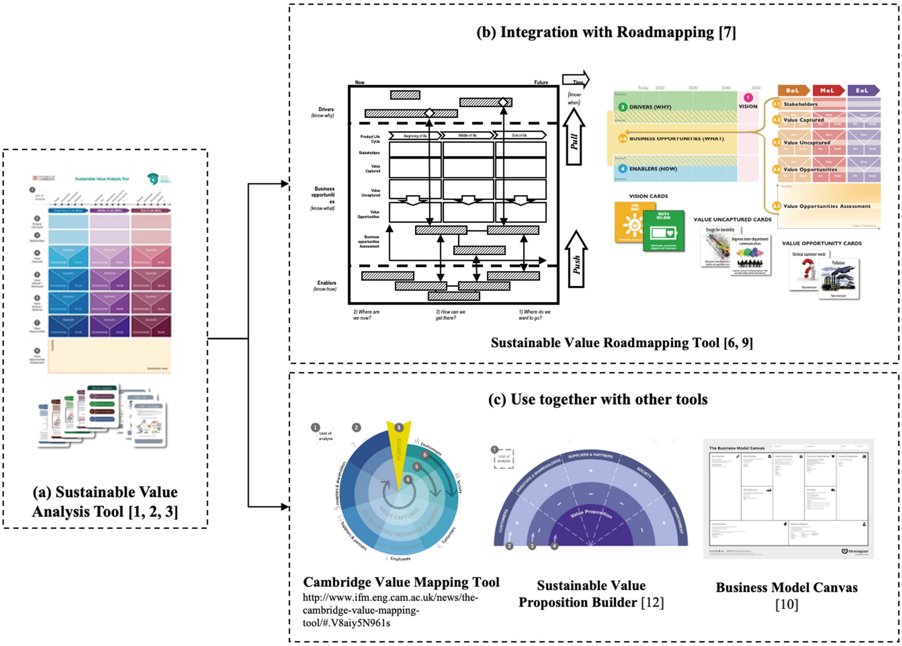


Fig. 1. Application of sustainable value analysis tool

3 Design of the Research Tool

3.1 Background of the Research Project

UK is a large shrimp consumption country, importing around US$ 850 million shrimp products every year, with around 53.2% from Southeast Asia, such as Indonesia, India, Vietnam, Bangladesh and Thailand [19]. According to the FAO [20], Indonesia is the fourth largest shrimp producer in the world. However, Indonesian Directorate General of Aquaculture reports that around 40% of shrimps in Indonesia are lost during the cultivation, production and logistics due to changing water quality, diseases and shrimp cannibalism. This has resulted in significant waste and affected food safety, e.g., due to bacteria in shrimps and the use of banned antibiotics. This research project aims to design digital solutions for improving the productivity, food safety and sustainability of shrimp industry in Indonesia. The specific purposes are to 1) identify the key challenges of productivity, food safety and sustainability in shrimp aquaculture industry in Indonesia, and 2) explore the applications of digital technologies (e.g., Internet of Things, big data, artificial intelligence, blockchain) to address these challenges.

In order to achieve the purposes of the research project, the team needs to collect empirical data from industrial partners in Indonesia, and co-design digital solutions for a more sustainable shrimp industry. Our research team consists of academics from interdisciplinary backgrounds in the UK, such as sustainability innovation, circular economy, operations/supply chain management, data science and aquaculture science. The industrial partners include various stakeholders from the Indonesian shrimp industry, including shrimp farmers, shrimp product manufacturer, middlemen, shrimp associations and government. The project requires strong engagement between the academics and industrial partners at the early stage. Due to the physical distance and different time zones between the two countries, it is challenging to have regular communication between the researchers and practitioners, which means there is limited time for data collection and engagement. Therefore, we realized that there is a strong need for an effective and efficient method for research data collection and industrial engagement.

3.2 Designing the Rationale

Since SVAT has been used for sustainability innovation in various research projects, we explored whether or not the concepts and rationale of SVAT could be adjusted and used for this research project. The general rationale of SVAT is that "*mapping the value uncaptured for all key stakeholders across the product life cycle can help organizations discover new opportunities for sustainable value creation*" (Fig. 2a). The requirement of this research tool is to co-design digital solutions for a more sustainable shrimp aquaculture industry in Indonesia. We adapted the life cycle thinking and stakeholder concepts from SVAT and adjusted the value logic to meet the specific requirement of this research project.

Combining the project requirement and the key concepts taken from SVAT, the rationale of this research tool is that "mapping the challenges for all key stakeholders across the shrimp life cycle can help organizations design digital solutions to address these challenges" (Fig. 2b). Some techniques, such as clustering, ranking and assessment, were also adjusted to design the detailed data collection process.

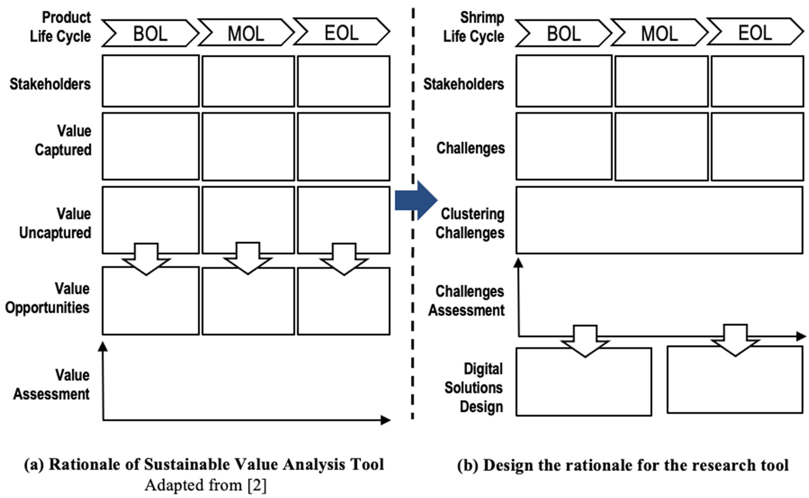
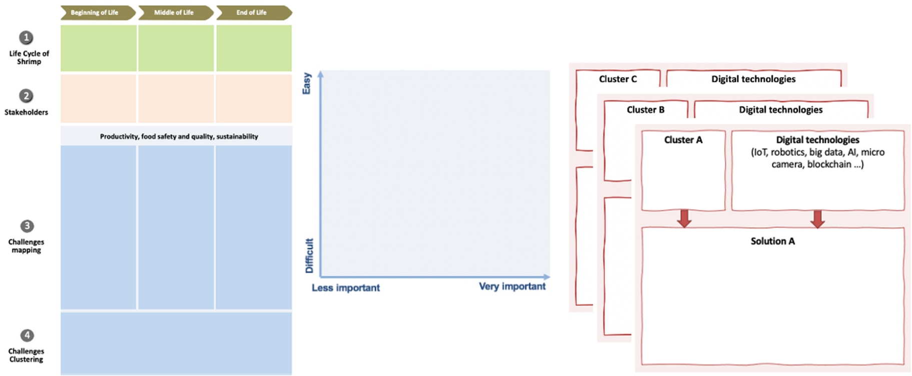


Fig. 2. Designing the rationale of the research tool

3.3 Designing the Research Tool

Based on the rationale, the research tool for this project is developed. The tool is composed of three parts, as is shown in Fig. 3: (a) mapping and clustering challenges, (b) assessing challenges, and (c) designing digital solutions. Design thinking techniques, such as clustering, dot-voting and 2 × 2 matrix, are used for these purposes.



(a) Map and cluster challenges **(b) Assess challenges** **(c) Design digital solutions**

Fig. 3. The research tool for the sustainable aquaculture project

The research tool is designed to be used in interactive workshops with industrial partners across aquaculture supply chains. Participants are guided to follow four steps to map the challenges on the first poster (Fig. 3a): 1) map the life cycle of shrimp, 2) map the stakeholders in each stage of shrimp life cycle, 3) map the key challenges for these stakeholders across the entire shrimp life cycle, considering the productivity, food safety and sustainability dimensions, and 4) cluster the identified challenges. The participants are guided to discuss and write ideas on post-it-notes and put them onto the related places of the posters. The facilitator plays an important role especially during the challenge clustering process.

The clustered challenges will be placed onto an empty poster. The participants will then be given dot labels with different colors representing the importance and easiness. Each participant needs to select three most important challenges and three most difficult challenges by placing different-colored dot labels in the relevant clusters. Then the clustered challenges will be placed in the second poster (Fig. 3b) for assessment. The most important challenge clusters (according to their easiness) will be moved to the digital solutions design posters (Fig. 3c), in which the data scientist takes a lead to co-design the digital solutions to address this challenge cluster.

3.4 Using the Research Tool

This research tool was used in a multi-stakeholder workshop in Sidoajo, Indonesia in August 2019. Participants include 12 industrial partners from Indonesia shrimp industry, including the governmental representatives from the Ministry of Marine Affairs and

Fisheries Republic of Indonesia, shrimp farmers, processors, shrimp and fishery associations, and fishery aquaculture researchers. The participants were divided into three groups with at least one facilitator or translator in each group. Each group followed the step-by-step process of the research tool within the group first, and then shared the data after each step, facilitated and coordinated by the lead researchers of the project. The industrial participants come from various stages of the shrimp life cycle, and they bring valuable, complementary expertise and knowledge to each process. Each group's data was shared and integrated after each step. Figure 4 shows the data collection through this research tool.

(1) Mapping the life cycle of shrimp
The participants mapped the entire life cycle of shrimp, from the brood stock, hatchery, post larva, cultivation, harvest; to shrimp processing, retailing, exporting, consumption; and to disposal.

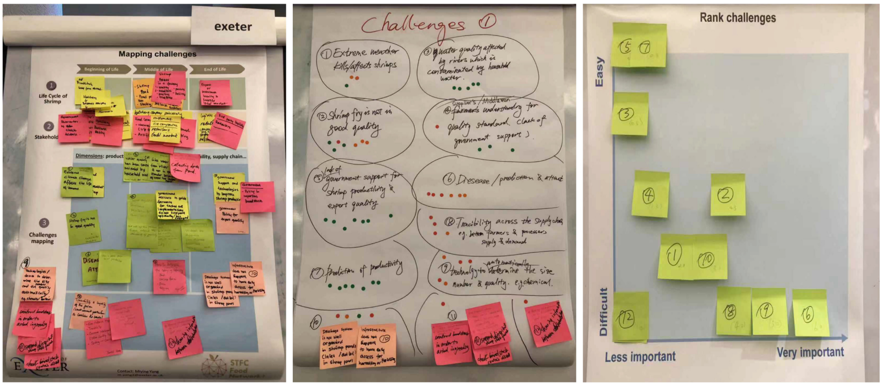
(2) Mapping the key stakeholders across the entire shrimp life cycle
The participants mapped the key stakeholders involved in each stage of the shrimp life cycle. A large number of stakeholders were identified, among which the main stakeholders include: government (local, EU/US, Japan), fishery department, ministry of trade, brood stock feeder, hatchery business entity, farmers, feed companies, artificial additive providers, middleman, shrimp and fishery association, shrimp processors, ice companies, shrimp processing equipment providers, international accrediting bodies, retailer, local market, logistic companies, end consumers, restaurant owners, shrimp shell recyclers, food waste collectors.

(3) Mapping and clustering life cycle challenges
The participants identified over 70 challenges across the entire shrimp life cycle from multiple stakeholders' perspectives (Fig. 4a), and clustered them into the following 12 types of challenges (Fig. 4b):

- Shrimp death due to extreme weather
- Low quality of shrimp fry
- Water quality affected by rivers and household waste and pollution
- Shrimp farmers and manufacturers' lack of understand quality standards
- Lack of government support for shrimp productivity and export quality
- Disease prevention/prediction
- Prediction of productivity
- Traceability across supply chain
- Lack of technology to automatically determine the shrimp size, quantity and quality
- Lack of infrastructure for shrimp pond (e.g., draining system)
- Spread and distribute the brood stock (e.g., to avoid inbreeding)
- Lack of information sharing and coordination among supply chain actors

(4) Assessing challenges
The challenges were assessed according to the importance and easiness, and we identified the six most important challenges (based on the result of dot voting) that can be taken into the next step. We analyzed the root causes of the challenges and

found that they share some common patterns, that is, they have the potential to be solved by a similar set of technologies. We then further grouped these challenges into two clusters (A and B). This clustering is based on whether or not these challenges could be solved by a similar set of technologies. Cluster A is that the lack of control of farming water quality causes the shrimp death and disease; and that the lack of technology to determine the shrimp size, number and quality causes the feeding problems, and therefore cannibalism. Cluster B is that the lack of the communication, collaboration, and support of the stakeholders across the entire shrimp supply chain.



(a) Mapping challenges (b) Clustering challenges (c) Assessing challenges

Fig. 4. Use of the research tool in the sustainable aquaculture project

(5) Co-design of the digital solutions for sustainable aquaculture
We further analyzed the Cluster A and Cluster B, and designed the conceptual solutions of using digital technologies (e.g. IoT, robotics, big data, AI, micro camera, blockchain) to address these challenges. The digital solution for Cluster A is to develop smart sensors and camera to monitor and predict the changes of water environment through real-time data collection and analysis. This can help shrimp farmers to prevent shrimp death from water changes or extreme weather, and provide them scientific feeding plans to reduce cannibalism. The digital solution for Cluster B is to develop a system which can improve the transparency and traceability of the entire shrimp supply chain, to improve the effectiveness and efficiency of communication among supply chain actors, and to reduce unnecessary costs and improve food safety. In particular, it is identified that the application of non-invasive sensor technologies and space geospatial data analytics can be used to monitor, predict the real-time environmental change of shrimp cultivation and production in Indonesian shrimp farming firms. Such applications can prevent the potential shrimp disease and death, improve food safety, maximize the shrimp quality and productivity, and reduce waste. These conceptual solutions provide the initial ideas of the prototype development in the later stages of the research project.

3.5 Feedback and Observation of Using the Research Tool

The 8-h workshop was recorded, and relevant data was transcribed and analyzed. The use of the research tool for industrial engagement received positive feedback from the industrial participants. First, all participants commented that the life cycle thinking of the research tool provided them a systematic, structured way to map and analyze the challenges across the entire life cycle of shrimp. The visualization of the tool helped them identify more challenges and see the connections between the challenges which were previously ignored. Second, the multi-stakeholder concept helped them better understand their stakeholders' challenges, which were not fully considered previously. Several industrial participants, for instance, mentioned that it is important to use the tool together with other supply chain partners, as the tool facilitates the communication that help them understand each other's challenges and concerns. An interesting observation is that they identified many stakeholders due to the life cycle thinking. They also found some common challenges between different stakeholders and the mutual interests in solving these challenges. Third, many participants mentioned that they were more willing to share their challenges and knowledge when using this visualized tool.

From the research perspective, we found that the research data collected through this tool is richer, more visual and comprehensive compared to the traditional semi-structured interviews especially when multiple stakeholders are engaged in the process.

4 Conclusion

This paper presents the design of a research tool for data collection and industrial engagement in a research project on sustainable shrimp aquaculture. This research project aims to explore digital solutions for improving sustainability of shrimp aquaculture industry in Indonesia. The project requires strong engagement with the industrial partners in Indonesia, including shrimp farmers, processors, middlemen and government. To better facilitate the research data collection and industrial engagement, the paper takes the concepts and techniques from the Sustainable Value Analysis Tool, and develop a new research tool for this project. The research tool was used in the workshop with industrial partners from various aquaculture organizations in Indonesia. The key challenges for different stakeholders across the shrimp life cycle were identified, clustered and assessed, based on which two digital solutions were co-designed to address these challenges. The results show that the empirical data collected through this way seem to be richer and more comprehensive compared to semi-structured interviews. It has also effectively helped the industrial partners to engage in the research process and co-design the practical solutions together with the academics.

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References

1. Yang, M.: Sustainable value analysis for product-service systems. PhD Thesis, University of Cambridge (2015)
2. Yang, M., Vladimirova, D., Evans, S.: Creating and capturing value through sustainability. Res. Manag. **603**, 30–39 (2017)
3. Yang, M., Evans, S., Vladimirova, D., Rana, P.: Value uncaptured perspective for sustainable business model innovation. J. Clean. Prod. **140**, 1794–1804 (2017)
4. Zacho, K.O., Mosgaard, M., Riisgaarrd, H.: Capturing uncaptured values — a Danish case study on municipal preparation for reuse and recycling of waste. Resour. Conserv. Recycl. **136**, 297–305 (2018)
5. Evans, S., Fernando, L., Yang, M.: Sustainable Value Creation—From Concept Towards Implementation. In: Stark, R., Seliger, G., Bonvoisin, J. (eds.) Sustainable Manufacturing. SPLCEM, pp. 203–220. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-48514-0_13
6. Yang, M., Despeisse, M.: Sustainable value roadmapping tool. In: R&D Management Conference, Cambridge, UK (2016)
7. Phaal, R., Farrukh, C.J.P., Probert, D.R.: Strategic roadmapping: a workshop-based approach for identifying and exploring strategic issues and opportunities. Eng. Manag. J. **19**, 3–12 (2007)
8. Dissel, M.C., Phaal, R., Farrukh, C.J., Probert, D.: Value roadmapping: a structured approach for early stage technology investment decisions. In: 2006 Technology Management for the Global Future – PICMET 2006 Conference, pp. 1488–1495. IEEE (2006)
9. Despeisse, Mélanie., Yang, M., Evans, S., Ford, S., Minshall, T.: Sustainable Value Roadmapping Framework for Additive Manufacturing. Procedia CIRP **61**, 594–599 (2017). https://doi.org/10.1016/j.procir.2016.11.186
10. Osterwalder, A., Pigneur, Y.: Clarifying business models: origins, present, and future of the concept. Commun. Assoc. Inform. Syst. **15**, 1–25 (2005)
11. Bocken, N.M.P., Short, S.W., Rana, P., Evans, S.: A value mapping tool for sustainable business modelling. Corp. Gov. **13**, 482–497 (2013)
12. Vladimirova, D.: Building sustainable value propositions for multiple stakeholders: a practical tool. J Bus. Model. **7**, 1–8 (2019)
13. Jun, H., Kiritsis, D., Xirouchakis, P.: Research issues on closed-loop PLM. Comput. Ind. **58**, 855–868 (2007)
14. Freeman, R.E.: Strategic Management: A Stakeholder Approach. Pitman, Boston, MA (1984)
15. Freeman, E.: Managing for Stakeholders: Survival Reputation and Success. Yale University Press (2007)
16. Argandoña, A.: Stakeholder theory and value creation (2011)
17. Elkington, J.: Cannibals with forks: the triple bottom line of 21st century business (1998)
18. Rana, P., Short, S., Evans, S.: D2.1 State-of-practice in business modelling and value-networks, emphasising potential future models that could deliver sustainable value (2012)
19. Pegg, S.: Market insight factsheet: prawn and shrimp (2019)
20. FAO: The state of food and agriculture: moving forward on food loss and waste reduction (2019)

PZT Based Active Microfluidic Droplet Generator for Lab-on-a-Chip Devices

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Abstract. The study presents the design and fabrication process of a novel microfluidic active droplet generator and development of a controller to actuate the integrated micropumps. The proposed active droplet generator consists of a droplet generation geometry and two microfluidic pumps to control the flow rate of the continuous phase fluid and the dispersed phase fluid to generate a microflow towards the droplet generation geometry. The droplet generator is developed based on flow-focusing geometry. Proposed micropumps have a pump chamber and a reservoir. A layer by layer method is adapted in fabricating the active droplet generator in which Polymethyl Methacrylate (PMMA) is used as the material. A heat treating based bonding method is discussed in combining fabricated PMMA layers together. Piezoelectric transducer, which is used as the actuator, is made of Lead Zirconate Titanate (PZT) and integrated into the micropump geometry to produce the microflow. The developed controller is capable of providing a range of shapes, frequencies, and amplitudes for the input signal leading to successful operations of the active droplet generator.

Keywords: Active droplet generator · Micropump · Microfluidic device fabrication · PZT based actuation · Lab on a chip

1 Introduction

Micro electro mechanical systems (MEMS) is an emerging technology which is widely applied in a variety of application areas in engineering disciplines such as automotive, biomedical, aerospace, and etc. At present, integration and miniaturization of functionalities related to biomedical systems, organs and laboratories are being thoroughly explored and have introduced system-on-a-chip, organ-on-a-chip, and lab-on-a-chip

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(LOC) research directions, respectively. LOC devices shrink two or more functions of a laboratory into one single chip which has the ability to perform point-of-care (POC) diagnostics [1]. LOC devices are a category of microfluidic devices which have the ability to manipulate small volumes of fluid. Polymerase Chain Reaction (PCR) test is one such LOC based diagnostic tool used to identify the Coronavirus in COVID-19 pandemic situation [2]. In performing laboratory test related tasks, LOC devices require various modules for sampling, transportation, preparation, separation, detection, and analysis. LOC devices related to sampling of fluids into small volumes is discussed in droplet based microfluidics, furthermore droplet generation and transportation is at interest due to the applicability in biomedical applications such as drug delivery systems, micro reactors, POC devices, drug encapsulation, etc. [3].

Droplet generation systems focus on creating discrete volumes of fluids using immiscible phase fluids enabling high throughput analysis and synthesis conditions of a large number of samples using a small volume. Additional advantages of microfluidics are operational flexibility, minimum material usage, higher resolution in separation, fast analysis, high detection sensitivity, and small footprints [4]. Three major techniques in microfluidics that use two-phase flow to generate droplets are digital microfluidics, gas-liquid, and liquid-liquid. Liquid-liquid technique omits the major drawback in digital microfluidics, which is the electrode size limits the generation of smaller droplets and only requires a system to generate microflows of one phase of matter which is liquid suitable for biomedical applications [5]. Depending on the generation method, droplet generators are mainly divided into two categories, as active and passive types. Active droplet generation requires an external power source to generate droplets, and by altering this input signal droplet manipulation is achievable [6]. Major parameters observed in droplet generation are droplet sizes and the generation frequency. T. Ward et al. presented a study on controllability of an automatic droplet generator based on droplet size and frequency [7]. Controllability is an important parameter of active droplet generators which is required in implementation of droplet generation modules to LOC devices. In liquid-liquid technique, controlling flow rates of the two immiscible liquids is important in formation of monodisperse droplets. Micropumps are capable of delivering fluid from one place to another in a controllable manner. Considering the various actuation mechanisms, micropumps are divided into mechanical type and non-mechanical type micropumps. Comparing the types of micropumps, non-mechanical micropumps limit its working fluid depending on the method that is used for actuation. Various studies on controlling micropumps are presented, and the micropumps use valves (active and passive) or fixed geometry (nozzle-diffuser, tesla valves, nozzle jet) based designs to control the fluid flow. Fixed geometry based (valveless) designs have comparative advantages such as durability, fabrication simplicity, and less complexity in controlling [8].

With advancements in micro scale fabrication technology, researchers have successfully implemented and developed numerous fabrication methods and processes in recent studies. Most of the microfluidic devices are fabricated using lithographic techniques. Polydimethylsiloxane (PDMS) is used as the substrate of the traditional microfluidic devices due to its biocompatibility and optical transparency. The photolithography process and the equipment used in the process is expensive as it requires infrastructure such as cleanroom facilities. Due to the limitations in lithographic techniques, prototyping of multilayer microfluidic chips is being investigated widely [9, 10]. Micromilling is one such alternative to photolithography as it is a fast and semi-automated process. Thermoplastics such as polycarbonate are widely used in micromilling based fabrication of microfluidic devices. CO_2 laser machining is also used for layer based fabrication techniques on polymers such as PMMA, PDMS and Polycarbonate for rapid production of microfluidic devices [11]. For successful functionality of microfluidic devices, damages to the channels have to be avoided in the fabrication process and the transparency of each layer has to be maintained for clear observation and detection. Vacuum heat press bonding, CO_2 gas solvent based bonding, and Isopropyl alcohol based bonding are several methods discussed in work related to layer by layer fabrication technique [12–14].

A PZT based active microfluidic droplet generator including valveless micropumps and a flow-focusing based droplet generation geometry is proposed in this study.

2 Proposed Design and Working Principle

Active droplet generation methods are mainly divided into two categories as methods based on additional forces and methods based on intrinsic forces. Centrifugal, magnetic, and electric forces based methods are examples discussed in literature for additional forces based methods. In regards to intrinsic forces based methods, the intrinsic forces generated by changing fluid velocity, and material properties such as viscosity, channel wettability, and density [15]. The proposed active droplet generation geometry includes two micropumps, and a droplet generator. In addition, the system consists of a main controller, function generator and an oscilloscope. Figure 1 shows the components of the proposed system for the study.

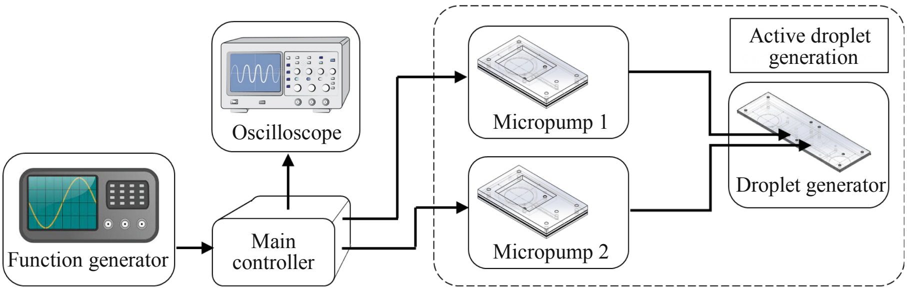

Fig. 1. Proposed system layout.

Among the aforementioned two types, the intrinsic method based on fluid velocity changing method is proposed for the study due to not having limitations on working fluid (as an example the magnetic forces based droplet generators require conductive fluid to generate a microflow) and less complexity in the development process. Therefore, it is required to deliver small volumes of continuous phase fluid and dispersed phase fluid to the microfluidic droplet generator in a controllable manner. A micropump is a device with a capability to deliver a small volume in a controllable manner. In this study two

Table 1. Categorization of micropumps.

Mechanical Micropumps		Non-Mechanical Micropumps	
Piezoelectric	Pneumatic	Hydrodynamic	Electroosmosis
Electrostatic	Thermal	Electrohydrodynamic	Electrowetting
Electromagnetic			

micropumps are used to control flow velocities of the continuous phase and dispersed phase. Table 1 presents a categorization of micropumps based on the actuation method.

The proposed micropump design belongs to the valveless nozzle jet type and also double diaphragm type. Main components of the micropump are the pump chamber and the reservoir. The significance is that the micropump was designed using a layer by layer method and is fabricated using the laser fabrication method. The pump chamber contains five layers and the reservoir contains three layers. The micropump design is presented in [16] as it is studied at a previous stage of the research.

The microfluidic channel provides a boundary for the microflow in the device, and its geometry has a direct impact on droplet generation. Cross-flow, co-flow, flow-focusing, and emulsification are the major four geometry types discussed in relation to droplet generation. Among these methods, flow-focusing geometry is recommended to produce comparatively smaller droplets [15]. In flow-focusing geometry based devices, the two immiscible fluids are hydrodynamically focused and thereafter elongated when passing through a contraction leading to generation of droplets. Figure 2 shows the schematic diagram of the droplet generation process in a flow-focusing based geometry.

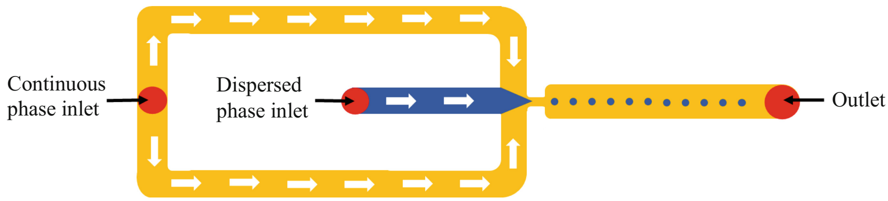

Fig. 2. Droplet generation based on flow-focusing geometry.

3 Design and Fabrication of the Active Droplet Generator

Initially, micropumps and the droplet generator geometry are designed as separate units, based on layer by layer method in a manner that a sequential bonding of the layers results in a single microfluidic device. Secondly, the designed layers are cut on clear acrylic sheets using laser cutting technique. Pump chamber and reservoir of each micropump are bonded as separate units in the process using heat treatment (HT) based bonding and later bonded together after gluing PZT discs. Finally, two micropumps are bonded on the bottom surface of the droplet generator geometry and the overall fabrication process is shown in Fig. 3. Layer by layer fabrication is considered as a thin film fabrication technique. Therefore, each layer of the design is modelled using SOLIDWORKS® software.

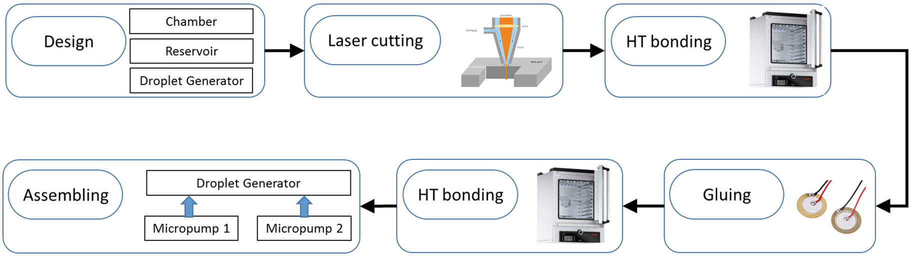

Fig. 3. Fabrication process.

Figure 4 shows the layers of the droplet generator, reservoir, pump chamber, and the complete assembly of the device. Inlet and outlet channels dimensions of the droplet generator are selected to reduce fluidic resistance.

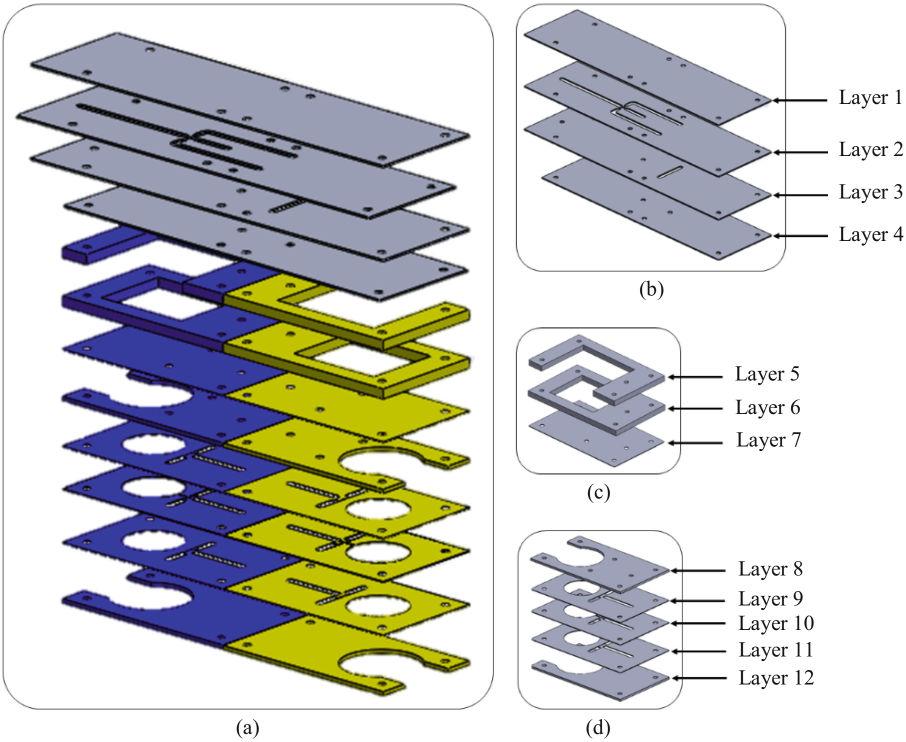

Fig. 4. Layer by layer design of the (a) Active droplet generator including two micropumps; (b) Droplet generator; (c) Reservoir; (d) Pump chamber.

Height of the inlet and outlet channels (shown in Fig. 5) are 1 mm and the width is 4 mm and 6 mm respectively. Height, width, and length of the contraction geometry are 1 mm, 1 mm, and 2.5 mm. Size of the droplet generation geometry is 220 mm × 60 mm × 4 mm. Considering the micropump, the cross section of the nozzle jet design is 1 × 0.3 (mm^2). Size of the micropump chamber is 100 mm × 60 mm × 7 mm and the volume of the reservoir is 10 cm^3. A layer with 5 mm thickness is added as the top layer of the reservoir to insert the fluid.

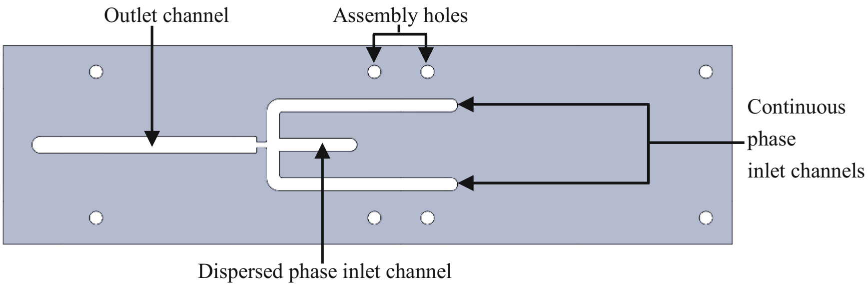

Fig. 5. Droplet generator layer design.

The nozzle jet type valveless micropump design has a minimum feature size of 300 μm at the nozzle end. Layer design with the nozzle jet geometry is shown in Fig. 6.

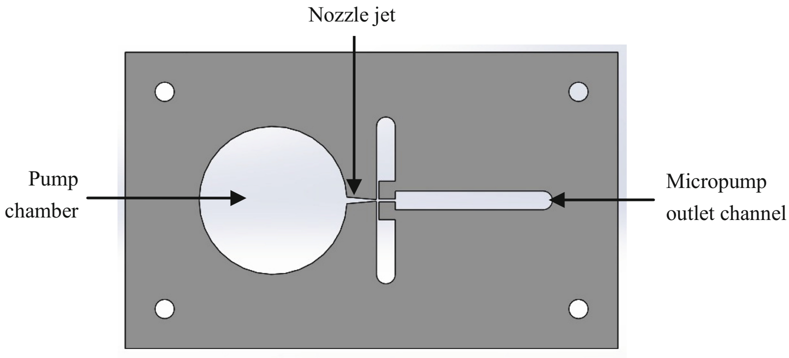

Fig. 6. Middle layer of micropump design.

The significance of layer by layer fabrication method is the ability to scale down to nanometer scale using silicon based MEMS fabrication technology. Due to the bio compatibility, transparency, cost effectiveness and availability, PMMA is selected for the fabrication of the active droplet generator. Additionally, using PMMA sheets as the material provides advantages in laser machining and assembling of microfluidic devices using layer bonding. Comparing layer by layer method with silicon deposition based fabrication, in the latter case requirements of advanced technology and equipment are significant. Therefore, each layer of the design is fabricated using PMMA sheets by laser machining and the layers after fabrication are shown in Fig. 7. RECI W4 laser cutting machine having a CO_2 laser tube is used and the power rating of the laser beam is 200 W.

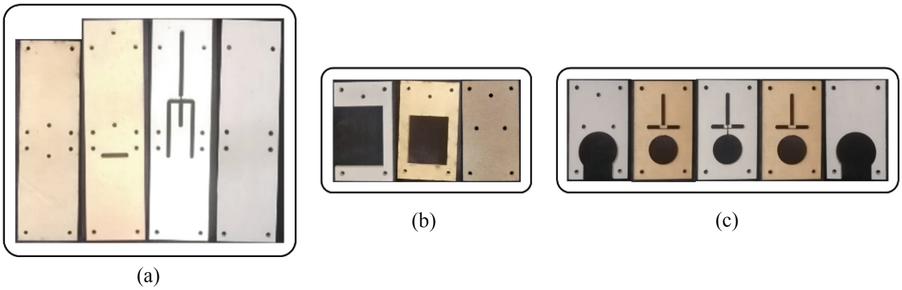

Fig. 7. Fabricated layers using laser machining technique (a) Droplet generator; (b) Pump reservoir; (c) Pump chamber.

PMMA sheets having 1 mm thickness are used for all layers of the droplet generator, layer two to four (from the bottom) of the pump chamber, and the bottom layer of the reservoir. Bottom layer and layer five belonging to the pump chamber use 2 mm thickness, and second and third layers from the bottom of the pump reservoir are fabricated using 5 mm PMMA sheets. Laser beam with a diameter of 0.02 mm is focused on the top surface of the PMMA sheet with a cutting power of 35 W. Cutting speeds are set to 20 mms^{-1}, 15 mms^{-1}, and 5 mms^{-1} are used for sheets having 1 mm, 2 mm, and 5 mm thicknesses respectively. A heat treatment based bonding technique is used to combine adjacent layers and the steps of the bonding process is shown in Fig. 8.

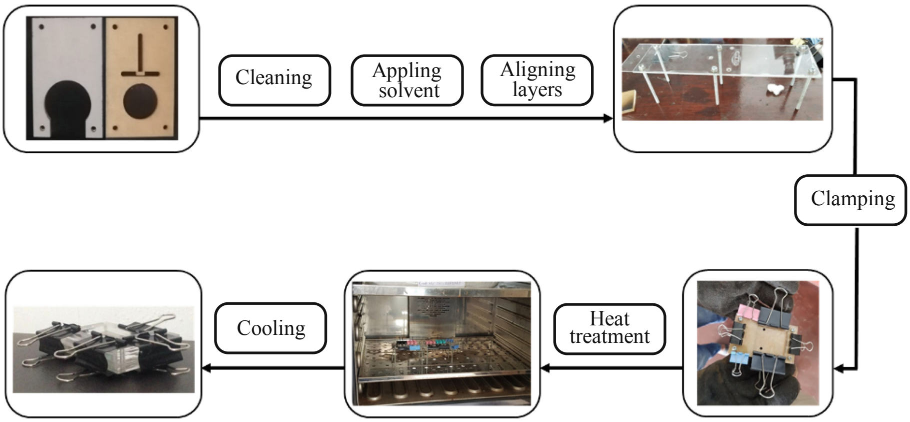

Fig. 8. Heat treatment based bonding process.

At the beginning of the bonding process, the PMMA sheets are thoroughly cleaned with 70% isopropyl alcohol. A thin film of solvent is added between the PMMA sheet surfaces and then layers are aligned sequentially and clamped onto each other using clamping clips before heat treating. Screw bolts are driven through the holes shown in

Fig. 4 and are fixed using nuts to ensure proper alignment of the layers. As the next step, fabricated layers are heat treated at 68 °C for 15 min using an electrical oven and are left to cool down to room temperature. After bonding the pump chamber, two piezoelectric discs are bonded on the top surface of layer 9 and bottom surface of layer 11 using Cyanoacrylate as the bonding medium. KBS-35DA-3A type piezoelectric transducers are used as PZT discs shown in Fig. 9.

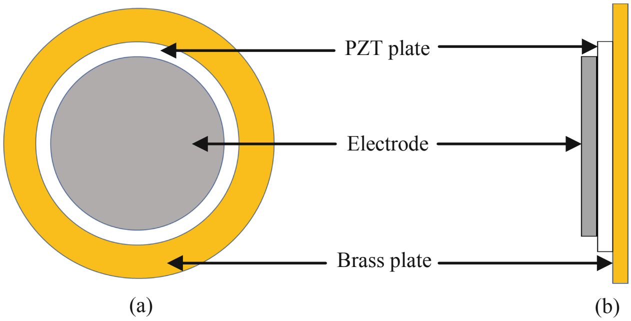

Fig. 9. Components of the piezoelectric transducer.

The diameter of the brass disc is 35.0 ± 0.1 mm and the thickness is 0.25 ± 0.03 mm. The PZT disc has a diameter of 25.0 ± 0.1 mm and a thickness of 0.53 ± 0.1 mm. The electrode disc diameter is 23.5 mm and a thickness similar to the PZT disc. Then, reservoir layers are bonded using the HT based bonding method as a separate unit. Similarly, the two fabricated micropumps are bonded with the droplet generator to form the device.

4 Development of the Controller

In controlling an active microfluidic droplet generator operating on fluid velocity changing methods using a flow-focusing geometry, the flow rate is the major parameter. In the proposed device, the flow rate is controlled by varying the actuating parameters of the integrated PZT disc. Therefore, a controller is developed to provide the flexibility in introducing various waveforms, input frequencies, and peak to peak voltages to the micropump which consists of two PZT discs. A function generator is used to introduce a range of frequencies and voltages whereas an oscilloscope is used to measure the output of the control circuit. Figure 10 presents a diagram that illustrates the hardware setup of the controller.

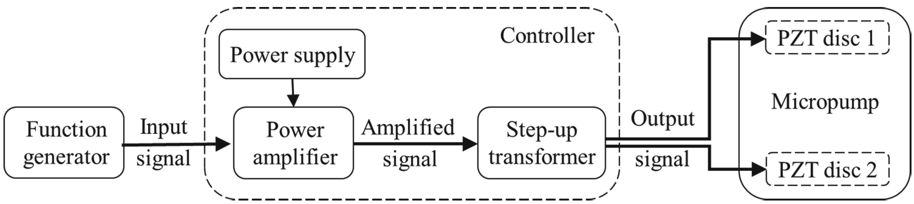

Fig. 10. Hardware setup for controlling.

The controller amplifies the input signal from the function generator and transmits the amplified signal to micropump through a step-up transformer to actuate the micropump. The developed main controller and electronic components are shown in Fig. 11.

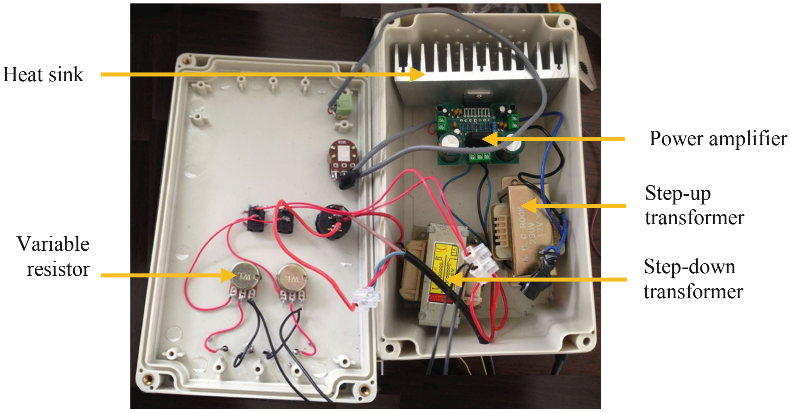

Fig. 11. Main controller.

Function generator (Tektronix AFG 2021) is able to generate sinusoidal, square and trapezoidal signals, ranging from 10 mV to 10 V in amplitudes and 1 μHz to 20 MHz in frequencies. A step-down transformer (1 A) is used to step down the 230 V to 18 V to power up the TDA7293 based power amplifier that amplifies the signal received from the function generator. Amplified signal is measured by using a digital oscilloscope (Tektronix TBS1102B-EDU).

5 Results and Discussion

The droplet generator and the two micropumps are assembled together successfully and the resulting device has a length, width and height of 200 mm, 60 mm, and 22 mm respectively. As a solvent assisted bonding process is used, the major issue occurred in fabrication is the incapability to bond PMMA sheets together in one step. The droplet generator design has layers with several designs which are different from adjacent layers, and it is difficult to clamp two layers with uniform surface contact. In addition, this issue is further enhanced with the increment in the number of layers. This leads to an uneven spread of the Isopropyl alcohol when sheets are bonded together as one single device resulting in voids which are unfavorable for the fluid flow in channels. Therefore, the bonding step needs several iterations to ensure successful bonding between layers and it is required to fill the voids with the solvent followed by heat treating. Micropump is fabricated by combining the layers of the pump chamber, reservoir, and two PZT elements and the fabricated micropump is shown in Fig. 12.

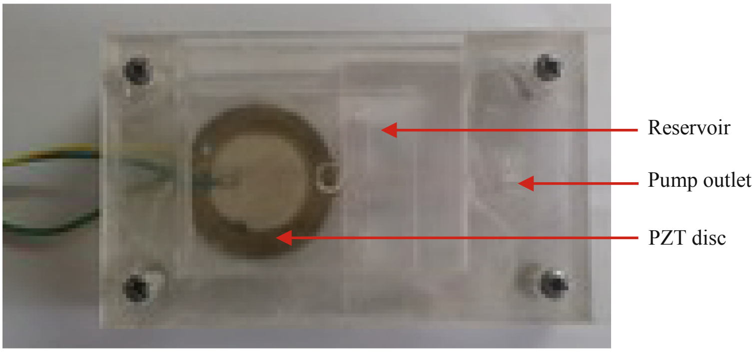

Fig. 12. Micropump after bonding process.

The Piezoelectric effect of the discs depends on the input voltage and the frequency of the signal. Initially, performance of a PZT transducer against a square, trapezoidal, and sinusoidal waveform is observed at an amplitude range of 10 mV to 3 V and a frequency range of 1 Hz to 300 Hz. When a square or a trapezoidal function is provided to the PZT element, there is noise due to sudden fluctuations in the input signal. Frequent failure of the PZT element is also experienced with aforementioned signal types. Conversely, when a sinusoidal waveform is selected a minimum distortion of the signal, noise, and failure is observed. It is observed that PZT elements require a smooth input signal for successful operation. The sinusoidal waveform is selected to the proper functionality of the droplet generator and an operating voltage range for a set of given frequencies is identified. In this regard, input voltage value is changed using the function generator where the frequency is set to a specific value at each test. Figure 13 shows the operating voltage range obtained in each test carried out for the frequency values 10 Hz, 15 Hz, 20 Hz, 25 Hz, 30 Hz, and 35 Hz.

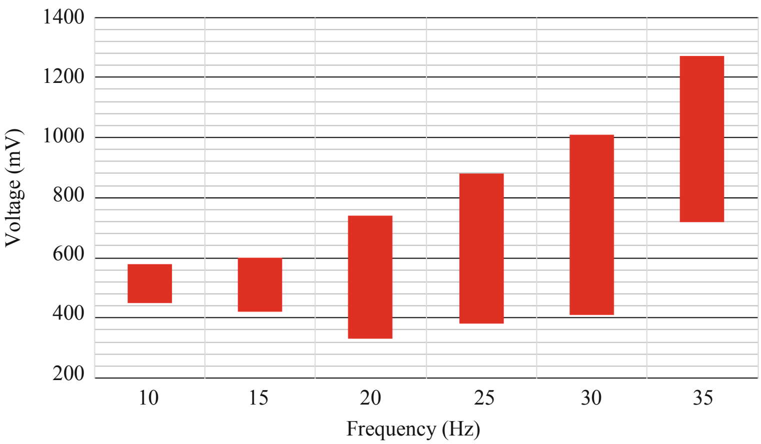

Fig. 13. Frequency vs. operating voltage.

No load conditions of the control circuit are tested to identify the cutoff region of the output signal when changing voltage and frequency of the input signal. The maximum output voltage of the TDA7293 based power amplifier is 50 V. At a constant frequency value of 100 Hz, the input peak to peak voltage value is decreased from 1.8 V to 1.3 V and the cut off region disappears at 1.6 V. Accordingly, the input voltage is maintained at or below 1.6 V. It is observed that the micropump is actuated at input voltage values greater than 100 V. Therefore, the maximum peak to peak output signal of the amplifier which is below 50 V is increased to a value above 100 V using a 12 V to 230 V full wave step-up transformer (1 A). Additionally, as the micropump is a double diaphragm type the actuating signal is provided at the same phase to achieve suction and compression pumping stages. To perform droplet generation, it is needed to actuate both pumps independently, therefore two similar controllers are required. Active microfluidic droplet generator is assembled by combining the two micropumps with the droplet generation layers as shown in Fig. 14.

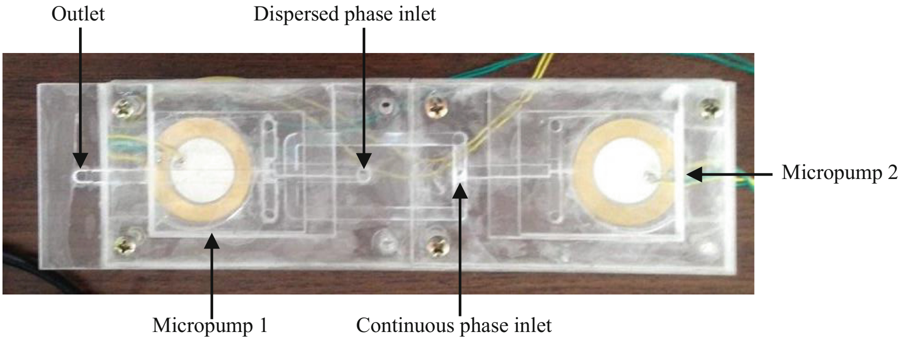

Fig. 14. Fabricated active microfluidic droplet generator.

Micropump 1 pumps the dispersed phase to the dispersed phase inlet channel which is located 15 mm above the pump outlet channel which is the layer 9 (shown in Fig. 4). Similarly, micropump 2 pumps the continuous phase to the continuous phase inlet channel located at a same height. Therefore, the pump head loss is neglected as it is considered to have similar effect in performance of both pumps. Due to the optical transparency provided by the PMMA material, PZT transducers are clearly visible to the top view of the device. Electrical connections are attached to avoid each inlet of micropumps and the outlet of the droplet generator to secure the device from contamination with the fluids.

6 Conclusion

A PZT based active droplet generator is successfully designed and fabricated with the capability to control the flow rates of continuous and dispersed phase fluids which is required to control the droplet sizes and generation frequency. The layer by layer method based fabrication technique proposed in the study is implemented for the components of the device including the droplet generator, micropump chamber, and reservoir. All the layers are fabricated using laser machining technology and combined using a heat treatment based bonding method. It is concluded that the layer by layer method together with laser cutting technology provides an effective combination in fabricating microfluidic devices. In this research, PMMA material is used to fabricate the layers of the active droplet generator. PMMA is considered 100% recyclable material and it is considered biodegradable. Therefore, this developed active droplet generator can be recyclable and biodegradable after its use. Significant importance of the sustainable designs are the minimalistic negative impact on the environment, hence usage of PMMA adds this advantage to the presented droplet generator. PZT based piezoelectric transducers are used to actuate the device and it is observed that the input signal with sinusoidal waveform performs smoother than square and trapezoidal waveforms in actuation. The developed controller possesses the ability to provide a sinusoidal waveform in a range of voltages and frequencies. Results show that the maximum voltage with reference to a given frequency increased.

In future, with the identified operating range of frequencies and the voltages of the micropumps, the droplet generator can be tested for different flow rates of dispersed and continuous phase fluids. Thereafter, the relationship between the diameter of the droplets formed and the droplet generation frequency can be studied with the flow rate ratios of the fabricated micropumps. To observe the effect of the surface roughness in generating droplets, application of surfactants on microchannel surfaces is required prior to the experimental procedures. Finally, the study will be directed towards the feasibility of integrating the PZT based active droplet generator to a Lab-on-a-chip device.

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References

1. Arshavsky-Graham, S., Segal, E.: Lab-on-a-chip devices for point-of-care medical diagnostics. Springer, Heidelberg (2020). https://doi.org/10.1007/10_2020_127
2. Tymm, C., Zhou, J., Tadimety, A., Burklund, A., Zhang, J.X.J.: Scalable COVID-19 detection enabled by lab-on-chip biosensors. Cell. Mol. Bioeng. **13**(4), 313–329 (2020). https://doi.org/10.1007/s12195-020-00642-z
3. Feng, H., et al.: Droplet-based microfluidics systems in biomedical applications. Electrophoresis **40**(11), 1580–1590 (2019). https://doi.org/10.1002/elps.201900047
4. Dressler, O.J., Maceiczyk, R.M., Chang, S.-I., DeMello, A.J.: Droplet-based microfluidics: enabling impact on drug discovery. J Biomol Screen **19**(4), 483–496 (2014). https://doi.org/10.1177/1087057113510401

5. Glawdel, T., Elbuken, C., Ren, C.L.: Droplet generation in microfluidics. encyclopedia of microfluidics and nanofluidics. In: Li, D. (ed.) Springer, Boston, pp. 1–12 (2013). https://doi.org/10.1007/978-3-642-27758-0_1713-1
6. Chong, Z.Z., Tan, S.H., Gañán-Calvo, A.M., Tor, S.B., Loh, N.H., Nguyen, N.-T.: Active droplet generation in microfluidics. Lab Chip **16**(1), 35–58 (2016). https://doi.org/10.1039/C5LC01012H
7. Gawel, D., Zawala, J.: Automatic single droplet generator with control over droplet size and detachment frequency. Colloids Interfaces **3**(3), 57 (2019). https://doi.org/10.3390/colloids3030057
8. Iverson, B.D., Garimella, S.V.: Recent advances in microscale pumping technologies: a review and evaluation. Microfluid Nanofluid **5**(2), 145–174 (2008). https://doi.org/10.1007/s10404-008-0266-8
9. Chen, X., Shen, J., Zhou, M.: Rapid fabrication of a four-layer PMMA-based microfluidic chip using CO_2 -laser micromachining and thermal bonding. J. Micromech. Microeng. **26**(10), 107001 (2016). https://doi.org/10.1088/0960-1317/26/10/107001
10. Sampath, W.H.P., Hettiarachchi, S.P., Melroy, N.H.R.G., Amarasinghe, Y.W.R.: Design and development of a droplet-based microfluidics system using laser fabrication machining techniques for a lab on a chip device. In: Chen, Y.-W., Tanaka, S., Howlett, R.J., Jain, L.C. (eds.) Innovation in Medicine and Healthcare. SIST, vol. 192, pp. 201–210. Springer, Singapore (2020). https://doi.org/10.1007/978-981-15-5852-8_19
11. Scott, S., Ali, Z.: Fabrication methods for microfluidic devices: an overview. Micromachines **12**(3), 319 (2021). https://doi.org/10.3390/mi12030319
12. Wang, J., Liu, G., Li, X., He, F., Ma, X.: A micromixer with two-layer crossing microchannels based on PMMA bonding process. Int. J. Chem.l Reactor Eng. **17**(8) (2019). https://doi.org/10.1515/ijcre-2018-0265
13. Wu, C.-L., Li, C.-C., Lu, C.-F., Yang, S.-Y.: Development of two step carbon dioxide assisted thermal fusion PMMA bonding process. Microsyst Technol **18**(4), 409–414 (2012). https://doi.org/10.1007/s00542-012-1427-y
14. Bamshad, A., Nikfarjam, A., Khaleghi, H.: A new simple and fast thermally-solvent assisted method to bond PMMA–PMMA in micro-fluidics devices. J. Micromech. Microeng. **26**(6), 065017 (2016). https://doi.org/10.1088/0960-1317/26/6/065017
15. Zhu, P., Wang, L.: Passive and active droplet generation with microfluidics: a review. Lab Chip **17**(1), 34–75 (2017). https://doi.org/10.1039/C6LC01018K
16. Munas, F., et al.: Development of PZT actuated valveless micropump. Sensors **18**(5), 1302 (2018). https://doi.org/10.3390/s18051302

Exploring the Risks of Blockchain and Circular Economy Initiatives in Food Supply Chains: A Hybrid Model Practice Framework

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Abstract. Food Supply Chains (FCSs) are center-stage in the global conversation on sustainability. The challenge of food loss and waste is prominent in the United Nations 2030 Agenda for Sustainable Goals, which demands halving the per capita global food waste at retail and consumer levels by 2030. Consumer awareness of food safety and health has also greatly increased in the last few decades; correspondingly, confidence in the quality of food has greatly decreased. Studies show that local and organic foods are perceived by consumers to be relatively healthier, and this new interest has led to academics and industry practitioners exploring a holistic understanding of FSCs a to tackle such emerging challenges. Several studies have examined FSCs through the lenses of circular economy principles, leading to the emerging term, circular food supply chains (CFSCs). Emergent digital technologies, including blockchain technologies (BCT), are touted to provide traceability, transparency and scalability which, if applied in FSCs, may help to address many of these challenges. However, the theory and technology of circular economy and BCT have, to-date, had only limited influence on FSCs due to inherent and/or perceived application risks. Further, there is a need for more considered and strategic integration of digital technologies, in general, as mechanisms for identify and mitigating potential risks, and achieving desired outcomes. Using a hybrid modelling approach of fuzzy set theory and interpretive structural modelling, this paper develops and proposes a framework in identifying and analysing these integration risks.

Keywords: Food supply chain · Blockchain technologies · Circular economy

1 Introduction

The efficient production, use, and consumption of food are closely tied to almost every one of the 17 Sustainable Development Goals (SDGs) outlined by the United Nations [1]. In fact, SDG 12.3, coordinated as the *Think.Eat.Save* program, specifically targets the reduction of food losses and wastes, including post-harvest losses, throughout production and supply chains, [2]. However, food supply chains (FSCs) are incredibly complex, distributed, and global in nature, with food items traveling thousands of miles

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around the world to be processed, manufactured, and/or otherwise modified, before they reach an individual's plate [3, 4]. The associated complexity and historic lack of transparency of FSCs has led to increased consumer awareness of the environmental impacts associated with food production and distribution [5–7]. Growing concern about the lack of transparency and the perceived declining quality of food has led to public calls for reliable FSC certifications in the hopes of new assurance of human and environmental safety [8–11]. With increasing pressure on both supply and demand sides of global food systems, academics and industry practitioners have begun to holistically examine FSCs to understand where human and environmental risks are being incurred, in the hopes of tacking both old and emerging challenges within conventional FSCs [12, 13].

Not surprisingly, the linear nature of FSCs have influenced whether and how environmental and human health challenges arise [14–16]. Adopting the industrial ecology analogy of "waste = food", several new studies attempt to re-examine FSCs through the lens of circular economy (CE) principles to explore the potential benefits and opportunities that may be derived by adapting FSCs to be more circular (Circular FSCs, or CFSCs) [17–19]. As with many circular supply chain analyses, the concept of CFSCs approaches circularity through a lens of "waste = food", and thus a "net-zero" waste objective [17]. To accomplish this format of circularity two strategies are proposed: First, FSC's must be designed so that at each stage there is no "waste" generated, i.e., by-products (valued, not wastes) are managed and cascaded within a bioeconomy system; and second; Collection and management systems that ensure effective cascading and use of these FSC by-products must be implemented [17, 20, 21].

Regardless of the degree of linearity vs. circularity of the FSC, issues of transparency and traceability remain of paramount concern if human and environmental health risks are to be effectively mitigated. The use of emergent digital technologies, such as blockchain technologies (BCT) are being investigated by major food producers and agri-businesses to assist with traceability within their supply chain [22]. BCT operates as a distributed, collective digital ledger or database into which relevant actions and transactions associated with an asset are recorded – effective 'blocks' of information, connected and structured into 'chains' of information [23]. It is the distributive nature of BCT that is purported to have the potential for enabling and facilitating greater transparency and trust within networks: as the database/ledger is available simultaneously to all users, information can be synchronized and available in real-time [24]. Once created, data cannot be changed by a single user, and information cannot be hidden [24]. Thus, the structure and rules for every blockchain can be adapted to the unique interests and needs of that particular asset, industry, supply-chain, or network [24–26]. Such distributed, secure, transparent, and customizable BCT technology presents many opportunities for industrial usage. Within supply chain applications there is a lot of interest and excitement regarding the potential for BCT to streamline and connect massive numbers of providers throughout globally dispersed, complex supply chains, and such streamlining (e.g., the reduction of paperwork) has been estimated to reduce the cost of transport by as much as 50% [27].

In the context of FSCs, the logic of visibility, transparency, and provenance that BCT can offer may be critical in markets with growing interest in the traceability from farm-to-table. If one can trace a contaminated produce back to its farm-of-origin, then the identification of other contaminated items that also originated from that same source can be done much faster, with greater confidence and reliability, and the high-risk items removed from retail shelves before they go home with a consumer [13, 14, 16, 22]. However, BCTs are incredibly powerful digital technologies that can offer FSCs so much more than just traceability from farm-to-table; BCT can be used to document 'hot-spots' within the FSC that may pose a greater risk, and thus support risk prevention strategies. When used appropriately and effectively, emergent digital technologies like BCT can facilitate traceability, transparency, and scalability across the FSC in ways that can alleviate health risks alongside food waste generation, and even identify opportunities for more circular and sustainable by-product use and management [13].

Unfortunately, both CE theory and BCTs are still in their infancy, and there is legitimate reluctance within industry to pursue their use due to inherent risks in application, and the lack of clear and concrete examples of optimized and effective systems that can be pointed to as models for 'success'. In many cases, there is a lack of clarity regarding exactly how BCT can be integrated into FSC's that require aggregation and/or blending of multi-sourced materials. Further complicating the digital transition of FSCs is the industry's decentralized, legacy infrastructure and systems that are often difficult and costly to overhaul [13, 17]. Accordingly, BCT and CE, despite their potential to address important human and environmental health considerations, have currently had only limited influence on FSC management, in-practice [13].

In the case of integrated CE principles and BCT, the inherent risks combined with the overwhelming complexity of FSCs in general, lead to a lack of understanding, consideration, and adoption [28, 29]. Compounding these concerns is an inherent assumption by academia that BCT innovation and adoption by FSCs will lead to sustainable outcomes; However, given the early stages of these digital technologies and their applications, a precautionary approach by industry may be most appropriate.

To explore the role of CFSCs and BCT as part of the strategy for achieving SDG 12.3, we use a hybrid modelling approach of fuzzy set theory and interpretive structural modelling to develop and propose a framework for identifying and analysing the associated inherent integration risks. From this framework, a model for risk analysis in the adoption of emerging digital technologies and CE theory to FSC evolution is presented to support and guide industry practitioners and new entrants into blockchain-enabled FSC operations.

2 Methodology

First a literature review is carried out on relevant papers within the following themes central to the paper: Blockchain, Circular Economy and Food Supply Chain on SCOPUS and Web of Science Database. From this literature we identify the risks for the integration of blockchain with CFSC. These includes scalability, storage, capacity, high development costs, lack of expertise, etc. [17, 30–32]. We further categorise these risks into five major groups, viz; implementation risks, managerial/organisational risks, technical risks, financial risks, market risks.

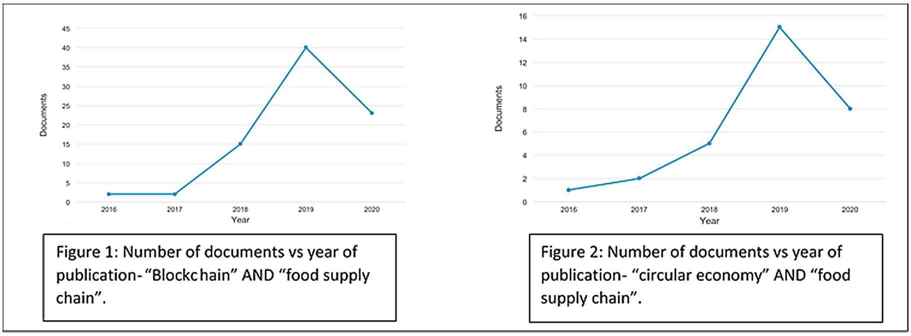

Fig. 1. SCOPUS capture of relevant search strings, "blockchain", "food supply chain" and "circular economy".

This traction is due to the growing interest in digital technologies, circular economy as well as the integrated area of these two research areas [33–35] even as circular economy continues to be emphasised as a sustainable model of triple bottom line value capture and retention within a closed loop of identified actors [36, 37]. From this literature we identified 25 sub-risks for the integration of blockchain with CFSC. These includes scalability, storage, capacity, high development costs, lack of expertise, etc. [17, 30–32]. These risks were then categorized into five major groups, viz; implementation risks, managerial/organisational risks, technical risks, financial risks, market risks.

In order to prioritise these risks, we develop a survey composed of questions developed on Qualtrics using the survey questionnaire protocol as defined in Robson and McCartan [38]. Here, the researchers specify and design the questions, the researchers then administer the questions, the respondents comprehend and answer the questions, the researchers recall the information and codes and analyse the data collected. In this way, this method "gets the cooperation of respondents and elicits accurate information" [38, 39]. The respondents are asked if they agree with the nomenclature and categories of these risks and are asked of their opinions which examines the significance of these risks in the integration of BCT and CFSC. Respondents are asked to choose from a "7-point" ranking system viz; "Very low significance", "Low significance", "Medium low significance", "Medium high significance", "High significance", "Very high significance". The choice of respondents was determined by their experience in BCT as applied in research and industrially. We had 21 respondents (academic and industry experts) with a minimum experience of 5 years and a maximum experience of 21 years. Following this, we clean and code the data on MS Excel and analyse it using Fuzzy Set Theory and Interpretive Structural Modelling (ISM).

2.1 Fuzzy Set Theory and Interpretive Structural Modelling Hybrid Method

The choice of a hybrid modelling method is driven by a number of reasons. In addition to the literature review and survey questionnaire a hybrid method has been used to analyse barriers and deal with vague decision making information, revealing the complex relationships amongst risks, in a direct, simple and visual way [40]. While available tools such as Fuzzy, ISM, TOPSIS and DEMATEL can analyse barriers and the relationships among them, the data set compiled from survey questionnaire and interviews present a challenge in manipulating the vagueness of people's judgements [41, 42]. Furthermore, several studies conclude that these methods (such as DEMATEL) do not consider the strength of risks on the relationships among the risks which can influence the accuracy of the results [40, 43]. A hybrid method is hence useful in solving the vagueness influence on decision making, improving the accuracy of the analysis results, reduces the biases of the experts and improves the accuracy of the model [40, 44].

Developed in 1965 by Zadeh [45] the fuzzy set theory is utilised to capture human qualitative judgements to support and solve decision-making problem. This is crucial in an organisational context which is often complex and requires complex processes due to the weakness in data and information, human subjectivity and the diverse linguistic judgments in humans [46]. The fuzzy set theory method combines the Fuzzy Delphi Method (FDM) and the Fuzzy Analytic Hierarchy Process (AHP). Binary numbers (0 and 1) are used to represent numbers which are specified as intervals [0, 1]. In very early studies, Dubois and Prade [47] further interpret that the fuzzy set based analysis can be shown as thus:

If ' X' describes a set of elements and the general component of is 'X' is expressed through 'x' having values(x_1, x_2, x_3,…..,x_n); the fuzzy set C for X is expressed as

$$\{(x, \mu_C(x))|x \in X\}$$

The membership of this fuzzy set C is defined through μ_C (x) [46]. We observe that the concept, the triangular fuzzy number (TFN), is most suited to pragmatic situations, such as supply chain research [48]. The membership function for the TFN (p,q,r) is calculated using the expression provided in Eq. (1). Fuzzy set theory and triangular fuzzy number provide a theoretical basis for the specific fuzzy calculation method used in this project which are, FDM and fuzzy AHP. A large number of formulas have been derived based on Eq. (1).

$$\mu_C(x) = \begin{cases} 0, & x \le p \\ \frac{x-p}{m-l}, & x \in [p, q] \\ \frac{x-r}{q-r}, & x \in [q, r] \\ 0 & otherwise \end{cases} \tag{1}$$

Following this, we utilise ISM as part of our hybrid tool. In an early definition, ISM is used for identifying and developing relationships among specific variables [49, 50]. It has also been described as a "well-known technique" for identifying the interrelationship between various connected parameters of a complex system [49]. Its relevance in examining complex system has ensured that the ISM has found usefulness in supply chain research [48, 51] as such, it is relevant to FSC studies [17]. Accordingly, ISM possesses the unique property of transferring vague mental models into a well-defined structure [52]. Hence, the ISM helps researchers in understanding inflicting order as well as the direction of complex relationships [52, 53]. Hence, ISM makes use of the graph theory or, more specifically, directed graphs (digraphs) to satisfy the requirements for the system composition and structure [50]. The ISM procedure can be achieved through the following steps (per [52]):

1) The constructs of the system which is being studied are identified and listed.
2) The identified constructs are evaluated to set up the contextual relationship. This relationship results in the formation of a "structural self-interaction matrix (SSIM)". This step provides all the visual demonstration of feedback from the expert. This is then processed to find the interrelationship of the identified risks [52, 54].
3) A binary matrix is developed from the SSIM. This is called the, "initial reachability matrix" (IRM).
4) The transitivity is evaluated in IRM. We obtain the "final reachability matrix" (FRM). This transitivity is important for finding any inconsistent data inputted by the experts [54]. Similar to Fuzzy set theory, expert opinion is a fundamental cornerstone to ISM.
5) The level-wise constructs are connected graphically. Direct links and transitive are dropped to get "Diagraph" and the final ISM model is obtained by replacing the nodes of the elements with names/statements.
6) To complete the modelling, the obtained model is evaluated for any conceptual disagreements and modified accordingly.

Generally, the ISM suffers from two principal limitations. It does not show the transitive links of factors in the hierarchical model [55]. Further, it offers no explanation of the reason behind the linkages with others. These limitations are solved through the "Total Interpretive Structural Model" (TSIM) [56]. For the purposes of this study, ISM is proposed but has not been completed as part of the hybrid model practice framework (Fig. 2).

3 Results and Discussion

3.1 The Hybrid Model Practice Framework

The integration of fuzzy set theory, specifically FDM and ISM, can help analyse, interpret, and model the priorities and relationships between identified risk criteria associated with BCT for CFSCs (hereafter "BCT-CFSC"). Accordingly, we propose a hybrid model practice framework that integrates both FDM and ISM to enable the integration of expert perspective and opinion, while also controlling for and mitigating issues of inconsistency or flawed logic that may present due to the qualitative and descriptive nature of the survey and interview process (Fig. 2).

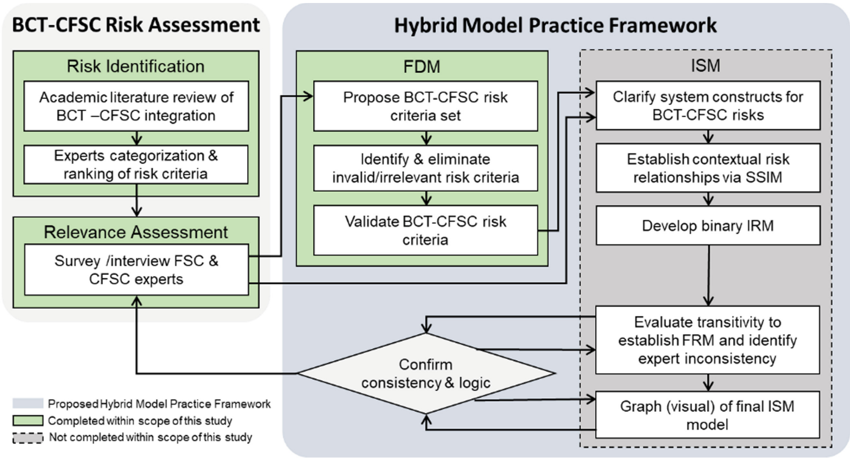

Fig. 2. Proposed Hybrid Model Practice Framework for the identification and assessment of risks associated with the integration of BCT and CFSCs.

3.2 Results of Fuzzy Delphi Model (FDM)

In staging for FDM (BCT-CFSC Risk Assessment – Fig. 2), the literature review revealed 25 risk criteria which were then categorized into six broader risk categories – security and laws [SL], funding [FD], technical [T], functional [FT], organizational [O], and business environment [BE] – as possible measurement attributes. Expert judgements and insights from the industry expert focus group surveys were used to develop TFNs for these 25 criteria based on the identified risk criteria. The FDM analysis was used to generate the relative importance and priority-status of each of the identified risk criteria, resulting in 23 risk considerations/criteria out of the initial 25 that could be used in the ISM tool (Table 1).

Completing the FDM analysis, Table 2 presents the local and global priority rankings for each category of BCT-CFSC integration risk, determined using FDM. From the risk category-level analysis, it is clear that operational [O] risks category is ranked as the highest risk priority with a weighting of 0.171, and that the lowest risk priority is the technical [T] category of risk, with a weighting of 0.160 (Table 2).

This analysis also highlights that there is very little difference in the range of weightings, with the second-rank risk priority (functional, [FT]) only 1.2% lower than operational risk priority (Table 2). Further, the difference between the third, fourth, and fifth-ranked risk categories is only a range of 0.6% (Table 2).

When ranked at the sub-risk criteria level, the results are modified somewhat, with security, compliance, and data privacy ranked as the top-three risk priorities that should be considered when integrating BCT and CFSCs (Table 3).

Table 1. Validated sub-risks for BCT-CFSC integration using FDM.

Category		Sub-risks	Methodology	References
[SL] Security and laws: Information security, privacy protection, regulations issues	1	Security (weaknesses and threats)	Qualitative thematic analysis; DEMATEL; case study approach	Reyna et al., (2018) [30] Tan et al., (2018) [57]; Kamilaris et al (2019) [31]; Tseng et al (2019) [58]
	2	Legal issues and Regulatory compliance		
	3	Anonymity and data privacy		
[FD] Funding: The cost of infrastructure needed to build the blockchain	4	Requiring costly new infrastructure	DEMATEL, ISM, AHP, analytic network process (ANP), structural equation modelling (SEM)	Andoni et al (2019) [59]; Farooque et al (2019) [17]; Kamilaris et al (2019) [31]
	5	High development costs for Blockchain technologies		
	6	High hardware and energy cost		
	7	Lack of investments funding		
[T] Technical: Key technical problems for the implementation of BCT	8	Consensus mechanism	Content-analysis based literature review; DEMATEL;	Farooque et al (2019) [17] Duan et al (2020) [60] Baralla et al (2019) [61]
	9	Computing (Processing) Power		
	10	Lack of consensus algorithm		
	11	Optimum platform/data-enabled infrastructure		
[FT] Functional: Functional challenges caused by the nature of BCT	12	Unreliable Speed	Qualitative thematic analysis; DEMATEL; case study approach	Farooque et al (2019) [17] Duan et al (2020) [60] Baralla et al (2019) [61]
	13	Continuously expanding ledgers		
	14	Scalability barrier		
	15	Implementation interoperability		
[O] Organizational: Cooperative relationships between organizations	16	Organisational resistance	Systematic literature review; DEMATEL;	Min (2019) [62], Farooque et al (2019) [17], Zhu et al, (2018) [32]
	17	Lack of Expertise		
	18	Changes in the ruling protocols		
	19	Lack of standardization and flexibility		
[BE] Business environment: Macro commercial and market environments	20	Lack of change drivers (policies, taxation, rewards)	DEMATEL, (ISM), systematic literature review.	Farooque et al (2019) [17]; Kamilaris et al (2019) [31]
	21	Lack of competitive advantage		
	22	Lack of proven commercial viability		
	23	Lack of Innovation and entrepreneurship		

Table 2. Results of FDM for local and global priority rankings of risk categories.

Risk category	Weight	Ranking
[SL] Security & laws	0.166	5
[FD] Funding	0.167	3/4
[T] Technical	0.160	6
[FT] Functional	0.169	2
[O] Operational	0.171	1
[BE] Business environment	0.167	3/4

Table 3. Results of FDM for global priority rankings of sub-criteria risk

		Sub-risks	Global priority	Global ranking
[SL]	1	Security (weaknesses and threats)	0.0588	1
	2	Legal issues and Regulatory compliance	0.0525	3
	3	Anonymity and data privacy	0.0548	2
[FD]	4	Requiring costly new infrastructure	0.0421	12
	5	High development costs for BCT	0.0407	19
	6	High hardware and energy cost	0.0412	16
	7	Lack of investments funding	0.0429	7
[T]	8	Consensus mechanism	0.0398	22
	9	Computing (Processing) Power	0.0421	13
	10	Lack of consensus algorithm	0.0403	21
	11	Optimum platform/data-enabled infrastructure	0.0378	23
[FT]	12	Unreliable Speed	0.0424	11
	13	Continuously expanding ledgers	0.0433	5
	14	Scalability barrier	0.0428	8
	15	Implementation interoperability	0.0406	20
[O]	16	Organisational resistance	0.0441	4
	17	Lack of Expertise	0.0428	9
	18	Changes in the ruling protocols	0.0433	6
	19	Lack of standardization and flexibility	0.0409	18
[BE]	20	Lack of change drivers (policies, incentives)	0.0426	10
	21	Lack of competitive advantage	0.0409	17
	22	Lack of proven commercial viability	0.0419	14
	23	Lack of Innovation and entrepreneurship	0.0416	15

3.3 Anticipated Results of Interpretive Structural Modelling (ISM)

As noted, this study does not present completed results from the ISM portion of the proposed hybrid framework (Fig. 2). However, it is expected that the inclusion of SSIM, IRM, FRM, and graphing of the relationships and transitivity between different BCT-CFSC integration risk criteria will bring further clarity to the rankings and prioritization of risk, as well as the clarification of vague/difficult to translate mental models of consulted experts. Thus, via the ISM portion of the proposed hybrid model practice framework, the following outcomes are anticipated:

1) The further clarifying the interrelationships between risk categories, criteria, and parameters delineated in the FDM stage to alleviate inherent challenges of complexity that may be uniquely present within CFSCs;
2) The transformation of vague mental models and assumptions inherent within the survey results and subsequent ranking of BCT-CFSC risk criteria, into well-defined structures that can convey a greater sense of order between priority rankings. E.g., aside from top-ranked risk category (operations) and the lowest-ranked risk category (technical), there is very little insight from FDM alone regarding whether and to what extent risks associated with funding, functional, and business environment considerations should be considered and explored further.
3) A diagrammatic (visual) representation of the relationships, the strength and directionality of those relationships, and the broader descriptive network of risk criteria that experts have associated with the integration of BCT-CFSC.

4 Limitations and Future Work

Given that this study does not yet incorporate the actual results of the hybrid Fuzzy-ISM methodology, comprehensive and validated findings from this exploration are not yet complete. Additional study is needed to understand whether, and to what extent unique portions of CFSCs may be affected differently (e.g., dairy vs. produce). As a core element of future work, the completion of ISM and comprehensive assessment of the integrated hybrid model findings are planned as the next stage of this research.

Fundamentally, significant questions remain as to whether BCT integration into CFSCs will provide meaningful value for suppliers throughout the CFSC value-chain. Further, it may be that the integration of BCT-CFSC solutions actually serve to compound risks associated individually with BCT or CFSCs alone. Thus, we recommend the advancement of more comprehensive research and evaluation of both benefit and risk of BCT-CFSC integration as per the precautionary principle, in advance of blind pursuit and adoption of BCT as the 'panacea' solution.

5 Conclusions

The present research is an effort to identify, analyse and understand the barriers of blockchain technology and circular food supply chains using a hybrid method of fuzzy set theory and interpretive structural modelling. Our analysis identified 23 different risks from literature as categorised under 6 different categories. Furthermore, while the security category remains highest in terms of risks, using FDM we do not find fundamental variations across identified risks with respect to prioritisation. We conclude by proposing a hybrid FDM-ISM methodology which will improve the accuracy of the results as well as help to proffer recommendations to industry practitioners wishing to adopt BCT in their food supply chain business.

References

1. United Nations: Transforming our world: the 2030 agenda for sustainable development. United Nations Publications (2016). https://doi.org/10.1201/b20466-7
2. Food and agriculture organization: Food wastage footprint: impacts on natural resources; summary report. natural resources management and environment department: Rome, Italy (2013)
3. Zhang, Y., Zou, T.: A review of food traceability in food supply chain'. Lecture Notes in Engineering and Computer Science, vol. 2228 (2017)
4. Gokarn, S., Kuthambalayan, T.S.: Analysis of challenges inhibiting the reduction of waste in food supply chain. J. Clean. Prod. Elsevier **168**, 595–604 (2017)
5. Kirwan, J., Maye, D., Brunori, G.: Acknowledging complexity in food supply chains when assessing their performance and sustainability. J. Rural Stud. Elsevier **52**, 21–32 (2017)
6. Hoelzer, K., Switt, A.I.M., Wiedmann, M., Boor, K.J.: Emerging needs and opportunities in foodborne disease detection and prevention: from tools to people. Food Microbiol. **75**, 65–71 (2018). Elsevier
7. Wilson, A.M., Withall, E., Coveney, J., Meyer, S.B., Henderson, J., McCullum, D., et al.: A model for (re) building consumer trust in the food system. Health Promot. Int. **32**(6), 988–1000 (2017)
8. Losasso, C., Cibin, V., Cappa, V., Roccato, A., Vanzo, A., Andrighetto, I., et al.: Food safety and nutrition: improving consumer behaviour. Food Control **26**(2), 252–258 (2012). https://doi.org/10.1016/j.foodcont.2012.01.038. Elsevier Ltd
9. Hobbs, J.E.: Consumer demand for traceability (2003)
10. Jensen, J.D., Christensen, T., Denver, S., Ditlevsen, K., Lassen, J., Teuber, R.: Heterogeneity in consumers' perceptions and demand for local (organic) food products. Food Qual. Prefer. **73**, 255–265 (2019). https://doi.org/10.1016/j.foodqual.2018.11.002. Elsevier
11. Krystallis, A., Chryssochoidis, G., Scholderer, J.: Consumer-perceived quality in 'traditional' food chains: the case of the Greek meat supply chain. Appetite **48**(1), 54–68 (. 2007). https://doi.org/10.1016/j.appet.2006.06.003
12. De Steur, H., Wesana, J., Dora, M.K., Pearce, D., Gellynck, X.: Applying value stream mapping to reduce food losses and wastes in supply chains: a systematic review. Waste Manage. Elsevier **58**, 359–368 (2016)
13. Chang, Y., Iakovou, E., Shi, W.: Blockchain in global supply chains and cross border trade: a critical synthesis of the state-of-the-art, challenges and opportunities. Int. J. Prod. Res. **58**(7), 2082–2099 (2020). Taylor & Francis
14. Sun, S., Wang, X.: Promoting traceability for food supply chain with certification. J. Clean. Prod. Elsevier **217**, 658–665 (2019)
15. Dabbene, F., Gay, P., Tortia, C.: Traceability issues in food supply chain management: a review. Biosyst. Eng. Elsevier **120**, 65–80 (2014)
16. Costa, C., Antonucci, F., Pallottino, F., Aguzzi, J., Sarriá, D., Menesatti, P.: A review on agri-food supply chain traceability by means of RFID technology. Food Bioprocess Technol. **6**(2), 353–366 (2013)

17. Farooque, M., Zhang, A., Liu, Y.: Barriers to circular food supply chains in China. Supply Chain Manage. 5. 677–696 (2019). https://doi.org/10.1108/SCM-10-2018-0345
18. Kazancoglu, Y., Ekinci, E., Mangla, SK., Sezer, MD., Kayikci, Y.: Performance evaluation of reverse logistics in food supply chains in a circular economy using system dynamics. Bus. Strategy Environ. **30**(1), 71–91 (2021). Wiley Online Library
19. Cicculo, F., Cagliano, R., Bartezzaghi, G., Perego, A.: Implementing the circular economy paradigm in the agri-food supply chain: the role of food waste prevention technologies. Resour. Conserv. Recycl. **164**, 105114 (2021). Elsevier
20. Mirabella, N., Castellani, V., Sala, S.: Current options for the valorization of food manufacturing waste: a review. J. Clean. Prod. Elsevier **65**, 28–41 (2014)
21. Kiser, B.: Circular economy: getting the circulation going. Nature **531**(7595), 443–446 (2016). https://doi.org/10.1038/531443a
22. Yiannas, F.: A new era of food transparency powered by blockchain. Innov. Technol. Govern. Global. **12**(1–2), 46–56 (2018). MIT Press
23. Rana, R.L., Tricase, C., De Cesare, L.: Blockchain technology for a sustainable agri-food supply chain. Emerald Publishing Limited, British Food Journal (2021)
24. Saberi, S., Kouhizadeh, M., Sarkis, J., Shen, L.: Blockchain technology and its relationships to sustainable supply chain management. Int. J. Prod. Res. **57**(7), 2117–2135 (2019). Taylor & Francis
25. Tasatanattakool, P., Techapanupreeda, C.: Blockchain: challenges and applications. In: 2018 International Conference on Information Networking (ICOIN), pp. 473–475. IEEE (2018)
26. Abou, J.J., Saade, R.G.: Blockchain applications–usage in different domains. IEEE Access **7**, 45360–45381 (2019)
27. Port of Antwerp: Antwerp start-up T-Mining develops Blockchain solution for safe, efficient container release | Port of Antwerp (2017). https://www.portofantwerp.com/en/news/antwerp-start-t-mining-develops-blockchain-solution-safe-efficient-container-release. Accessed 27 May 2021
28. Malhotra, A., O'Neill, H., Stowell, P.: Thinking Strategically About Blockchain Adoption Risks And Risk MitigatioN. Elsevier, Business Horizons (2021)
29. Lindman, J., Tuunainen, V.K., Rossi M.: Opportunities and risks of blockchain technologies–a research agenda (2017)
30. Reyna, A., Martín, C., Chen, J., Soler, E., Díaz, M.: On blockchain and its integration with IoT. challenges and opportunities. Future Gener. Comput. Syst. **88**(2018), 173–190 (2018). https://doi.org/10.1016/j.future.2018.05.046
31. Kamilaris, A., Fonts, A., Prenafeta-Boldύ, F.X.: The rise of blockchain technology in agriculture and food supply chains. Trends Food Sci. Technol. **91**, 640–652 (2019). https://doi.org/10.1016/j.tifs.2019.07.034
32. Zhu, Z., Chu, F., Dolgui, A., Chu, C., Zhou, W., Piramuthu, S.: Recent advances and opportunities in sustainable food supply chain: a model-oriented review. Int. J. Prod. Res. **56**(17), 5700–5722 (2018). https://doi.org/10.1080/00207543.2018.1425014. Taylor & Francis
33. Okorie, O., Salonitis, K., Charnley, F., Moreno, M., Turner, C., Tiwari, A.: Digitisation and the circular economy: a review of current research and future trends. Energies **11**(11), 3009 (2018). https://doi.org/10.3390/en11113009
34. Tseng, M.L., Tan, R.R., Chiu, A.S.F., Chien, C.F., Kuo, T.C.: Circular economy meets industry 4.0: can big data drive industrial symbiosis? Resour. Conserv. Recycl. **131**, 146–147 (2018;). https://doi.org/10.1016/j.resconrec.2017.12.028. Elsevier
35. Makov, T., Vivanco, D,F.: Does the circular economy grow the pie? The case of rebound effects from smartphone reuse. Front. Energy Res. **6**, 1–11 (2018). https://doi.org/10.3389/fenrg.2018.00039
36. Rajput, S., Singh, S,P.: Connecting circular economy and industry 4.0. Int. J. Inf. Manage. **49**, 98–113 (2019). https://doi.org/10.1016/j.ijinfomgt.2019.03.002. Elsevier

37. Kiser, B.: Circular economy: getting the circulation going. Nature **531**, 443–446 (2016)
38. Robson, C., McCartan, K.: Real world research: a resource for users of social research methods in applied settings. 4th edn, p. 560. Wiley, West Sussex (2016)
39. Yin, R,K.: Case study research. design and methods. 5th edn. SAGE Publications, Thousand Oaks (2014)
40. Song, W., Zhu, Y., Zhao, Q.: Analyzing barriers for adopting sustainable online consumption: a rough hierarchical DEMATEL method. Comput. Ind. Eng. **140**(37), 106279 (2020). https://doi.org/10.1016/j.cie.2020.106279. Elsevier
41. Ganguly, K.K., Das, D.: Analysing the barriers in Indian stone crushing industries: an ISM and fuzzy AHP approach. Int. J. Appl. Manage. Sci. **12**(3), 242–264 (2020). https://doi.org/10.1504/IJAMS.2020.108072
42. Han, Y., Deng, Y.: A hybrid intelligent model for assessment of critical success factors in high-risk emergency system. J. Ambient. Intell. Humaniz. Comput. **9**(6), 1933–1953 (2018). https://doi.org/10.1007/s12652-018-0882-4
43. Gardas, B.B., Raut, R.D., Narkhede, B.: Evaluating critical causal factors for post-harvest losses (PHL) in the fruit and vegetables supply chain in India using the DEMATEL approach. J. Clean. Prod. **199**, 47–61 (2018). https://doi.org/10.1016/j.jclepro.2018.07.153. Elsevier Ltd
44. Gardas, B.B., Raut, R.D., Narkhede, B.: Identifying critical success factors to facilitate reusable plastic packaging towards sustainable supply chain management. J. Environ. Managem. **236**, 81–92 (2018). https://doi.org/10.1016/j.jenvman.2019.01.113. Elsevier
45. Zadeh, L.A.: Fuzzy sets. Inf. Control. **8**, 338–353 (2019). https://doi.org/10.1201/9780429287831-2
46. Kumar, A., Zavadskas, E.K., Mangla, S.K., Agrawal, V., Sharma, K., Gupta, D.: When risks need attention: adoption of green supply chain initiatives in the pharmaceutical industry. Int. J. Prod. Res. **57**(11), 3554–3576 (2019). https://doi.org/10.1080/00207543.2018.1543969. Taylor & Francis
47. Dubois, D., Prade, H.: Fuzzy real algebra: some results. Fuzzy Sets Syst. **2**, 327–348 (1979)
48. Mangla, S.K., Kumar, P., Barua, M.K.: An integrated methodology of FTA and fuzzy AHP for risk assessment in green supply chain. Int. J. Oper. Res. **25**(1), 77–99 (2016)
49. Warfield, J.N.: Developing subsystem matrices in structural modeling. IEEE Trans. Syst. Man Cybern. **SMC-4**(1), 74–80 (1974).https://doi.org/10.1109/TSMC.1974.5408523
50. Watson, R.H.: Interpretive structural modeling-a useful tool for technology assessment? Technol. Forecast. Soc. Change **11**(2), 165–185 (1978). https://doi.org/10.1016/0040-1625(78)90028-8
51. Mangla, S.K., Luthra, S., Mishra, N., Singh, A., Rana, N.P., Dora, M., et al.: Barriers to effective circular supply chain management in a developing country context. Prod. Plann. Control **29**(6), 551–569 (2018). https://doi.org/10.1080/09537287.2018.1449265. Taylor & Francis
52. Raut, R.D., Yadav, V.S., Cheikhrouhou, N., Narwane, V.S., Narkhede, B.E.: Big data analytics: implementation challenges in Indian manufacturing supply chains. Comput. Ind. **125**, 103368 (2021). https://doi.org/10.1016/j.compind.2020.103368. Elsevier B.V.
53. Gardas, B.B., Raut, R.D., Cheikhrouhou, N., Narkhede, B.E.: A hybrid decision support system for analyzing challenges of the agricultural supply chain. Sustain. Prod. Consumpt. **18**, 19–32 (2019). https://doi.org/10.1016/j.spc.2018.11.007. Elsevier B.V
54. Sarkar, A., Qian, L., Peau, A.K., Shahriar, S.: Modeling drivers for successful adoption of green business: an interpretive structural modeling approach. Environ. Sci. Pollut. Res. **28**(1), 1077–1096 (2020). https://doi.org/10.1007/s11356-020-10490-z
55. Swarnakar, V., Singh, A.R., Antony, J., Kr Tiwari, A., Cudney, E., Furterer, S.: A multiple integrated approach for modelling critical success factors in sustainable LSS implementation. Comput. Ind. Eng. **150**, 106865 (2020). https://doi.org/10.1016/j.cie.2020.106865. Elsevier Ltd

56. Sushil, S.: Interpreting the interpretive structural model. Global J. Flexible Syst. Manage. **13**(2), 87–106 (2012). https://doi.org/10.1007/S40171-012-0008-3
57. Tan, B., Yan, J., Chen, S., Liu, X.: The impact of blockchain on food supply chain: the case of walmart. In: Qiu, M. (ed.) SmartBlock 2018, pp. 167–177. Springer, Cham (2018). https://doi.org/10.1007/978-3-030-05764-0
58. Tseng, M.L., Chiu, A.S.F., Chien, C.F., Tan, R.R.: Pathways and barriers to circularity in food systems. Resour. Conserv. Recycl. **143**, 236–237 (2019). https://doi.org/10.1016/j.resconrec.2019.01.015. Elsevier
59. Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., et al.: Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renew. Sustain. Energy Rev. **100**, 143–174 (2019). https://doi.org/10.1016/j.rser.2018.10.014. Elsevier Ltd
60. Duan, J., Zhang, C., Gong, Y., Brown, S., Li, Z.: A content-analysis based literature review in blockchain adoption within food supply chain. Int. J. Environ. Res. Publ. Health (2020). https://doi.org/10.3390/ijerph17051784
61. Baralla, G., Ibba, S., Marchesi, M., Tonelli, R., Missineo, S.: A blockchain based system to ensure transparency and reliability in food supply chain. In: Mencagli, G., et al. (eds.) Euro-Par 2018. LNCS, vol. 11339, pp. 379–391. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-10549-5_30
62. Min, H.: Blockchain technology for enhancing supply chain resilience. Busin. Horizons. Kelley School of Business, Indiana University **62**(1), 35–45 (2019). https://doi.org/10.1016/j.bushor.2018.08.012

Human Activity Recognition Using K-Nearest Neighbor Machine Learning Algorithm

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Abstract. Smart factory in the era of Industry 4.0 requires humans to have continuous communication capabilities among each other's and with the existing smart assets in order to integrate their activities into a cyber-physical system (CPS) within the smart factory. Machine learning (ML) algorithms can help precisely recognize the human activities, provided that well-designed and trained ML algorithms for high performance recognition are developed. This paper presents a k-nearest neighbor (KNN) algorithm for classification of human activities, namely Laying, Downstairs walking, Sitting, Upstairs walking, Standing, and Walking. This algorithm is trained and the algorithm's parameters are precisely tuned of for high accuracy achievement. Experimentally, a normalized confusion matrix, a classification report of human activities, receiver operating characteristic (ROC) curves, and precision-recall curves are used to analyze the performance of the KNN algorithm. The results show that the KNN algorithm provides a high performance in the classification of human activities. The weighted average precision, recall, F1-score, and the area under the micro-average precision-recall curve for the KNN are 90.96%, 90.46%, 90.37%, and 96.5%, respectively, while the area under the ROC curve is 100%.

Keywords: Machine learning · KNN · Human activity recognition · Industry 4.0

1 Introduction

The fourth industrial revolution (Industry 4.0) is characterized by the internet of things (IoT), cyber-physical systems, big data, and artificial intelligence (AI), which had a vital impact in smart manufacturing processes [1]. Moreover, humans in a smart factory being are primarily responsible for the manufacturing processes. So, should be classify human activities to know the efficiency of the humans during the manufacturing. In other words, with the recent digital transformation associated with the exponential growth of information and communication-driven technologies it is essential to seamlessly identifying

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human activities in smart factories [2, 3]. One of the utilized devices for measurement and detection of human activities are accelerometers, which are used in hospitals to detect patients status [4]. However, to some extent commercially available accelerometers have limited accuracy, which is consider an issue to be addressed [5, 6]. More accurate recognition of human activities is solved via a vision technology, such as digital cameras [7–9], but this method cannot always achieve a satisfactory performance of accuracy [10, 11]. Machine learning algorithms, such as K-nearest neighbors (KNN_S) contributes to a promising solution to solve the low accuracy issue. KNN algorithms have already shown high feasibility in fields such as facial recognition, text mining and potentially applicable for identifying human activities as well.

In the literature, a number of machine learning algorithms have been presented for classification of human activities. Chen and Shen [12] introduced a random forest (RF) algorithm to classify human activities, this algorithm used an accelerometer with a gyroscope to capture the data, this algorithm was applied on a dataset consisting of 27,681 samples and reached a total accuracy of 83.59%. In [13], Fen *et al.* proposed a J48 algorithm with a smartphone with built-in accelerometers for daily life activities. It was applied on a dataset contains 8,097 data samples and had an accuracy of 89.6%. Ling and Wang [14] presented a design of a decision tree (DT) algorithm for human activity identification, this design was used with only four activities of sitting, walking, standing, and running and it achieved an 73.72% testing accuracy. Girja *et al.* [15] introduced a naive bayes (NB) algorithm to recognize human activity. This algorithm was also applied to the UCI-HAR dataset [16] and reached an overall accuracy of 79%. In [17], Bao and Intille proposed an algorithm to recognize human activities. It used a DT algorithm with 5 accelerometers. It divided 5 activities reached an accuracy of 84.0%.

Looking the reviewed literature, one can argue that although KNN algorithm has shown high potential to address the accuracy issue in detecting human activities, however they reached performance has not been yet up to the bar. In this context, this paper presents an enhanced KNN algorithm to classify human activities, namely Laying, Downstairs, Sitting, Upstairs, Standing, and Walking, with an objective of increasing the classification accuracy of the algorithm via a fine tuning for the parameters of algorithm. This algorithm is evaluated using metrics of the precision, F1-score, area under the precision-recall curve. The algorithm is applied to the HAR dataset [16]. The main contributions of the paper are the following: (i) Implementing of an enhanced KNN algorithm with fine-tuned parameters to classify human activities, (ii) Evaluating the performance of the implemented algorithm for various evaluation metrics using the HAR dataset.

The remainder of the paper is organized as follows: Sect. 2 presents the proposed machine learning algorithm with the dataset description. The experimental results are reported in Sect. 3 and discussed in Sect. 4. Finally, conclusion is drawn in Sect. 5.

2 Proposed Algorithm

Figure 1 shows the structure of the proposed KNN algorithm. It is implemented using Scikit-learn framework. It consists of five steps: the first step is a pre-processing using filters to remove the noise from the utilized dataset, the second step is a feature extraction of the dataset. So, 561 features are extracted with fixed windows of 2.56 s "128 readings per window". The dataset features are a_x, a_y, and a_z, which represent the accelerations in the x-axis, y-axis, z-axis, respectively. Also, another extracted features of the dataset are g_x, g_y, and g_z, which represent the gyroscope angles. The third step is the selection of a specific feature, the fourth step is the training on the dataset, and the fifth step is the testing/classification for the activities. Figure 2 illustrates a mechanism of the KNN algorithm. For instance, it assumes two categories or classes "A and B" and a new data point x_1 which colored blue. So, the KNN algorithm can detect the data point in which category will be lied. This algorithm uses neighbors' number of 20 and it is based on the Euclidean distance (d_E), which is computed between a two categories "points", where d_E is represented in Eq. (1). In this algorithm, a neighborhood function is used to classify the activities. The best selection of k depends on the dataset. So, the largest k reduces the noise applied to a classification. Furthermore, the KNN is a supervised machine learning algorithm used to obtain the nearest data point from the same class and nearest data from different classes. The dataset used for the classification is the UCI-HAR dataset available in [16]. It consists of 748,406 samples of different activities Laying, Downstairs, Sitting, Upstairs, Standing, and Walking. The sample percentage for each activity are 18.3%, 14.4%, 16.9%, 15.6%, 18.5%, and 16.3%, respectively. The dataset are gathered from 30 individuals using a mobile phone (Samsung Galaxy S II), which includes inertial sensors positioned in a waist. The dataset readings are extracted with a 50 Hz sampling rate. The dataset has 6 attributes with information correlated to the activities of the humans' activities: time and x-, y-, z-accelerations. The dataset is divided into an 70% training set and a test set of 30%. The test set is utilized to evaluate the proposed algorithm.

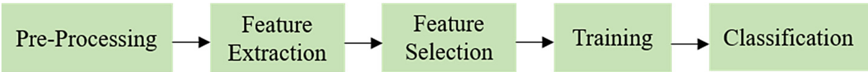

Fig. 1. The proposed KNN algorithm structure.

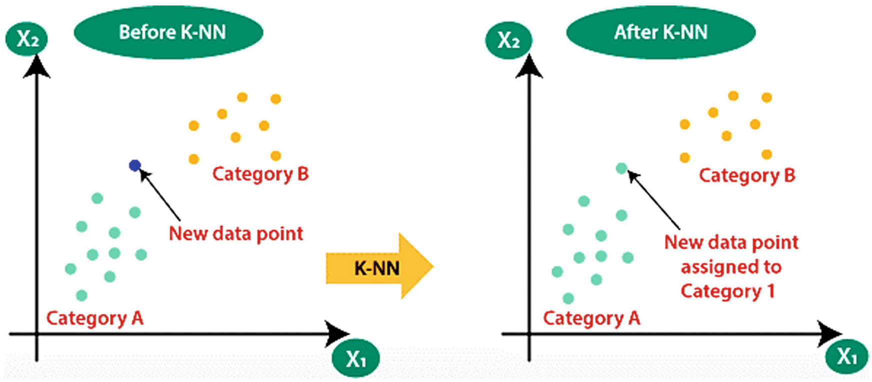

Fig. 2. The mechanism of the KNN algorithm.

$$d_E(x, y) = \sqrt{\sum_{i=1}^{n} (x_1 - y_1)^2} \quad (1)$$

3 Results

Figure 3 shows the testing accuracy curve of the KNN algorithm. This curve continuously changes and reaches a maximum value of 90.46% after 20 neighbors. Figure 4 shows the testing loss curve of the KNN algorithm. The loss rate continuously decreases with increasing number of neighbors. The loss rate reaches 9.54% after 20 neighbors.

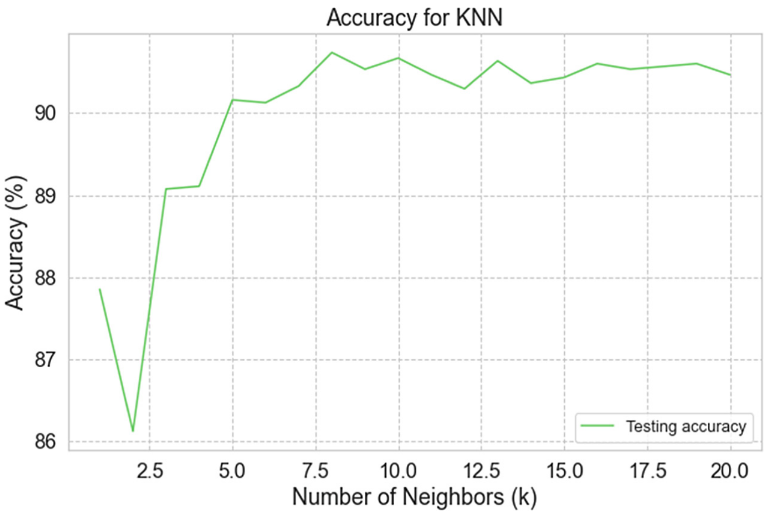

Fig. 3. The testing accuracy curve for the KNN algorithm.

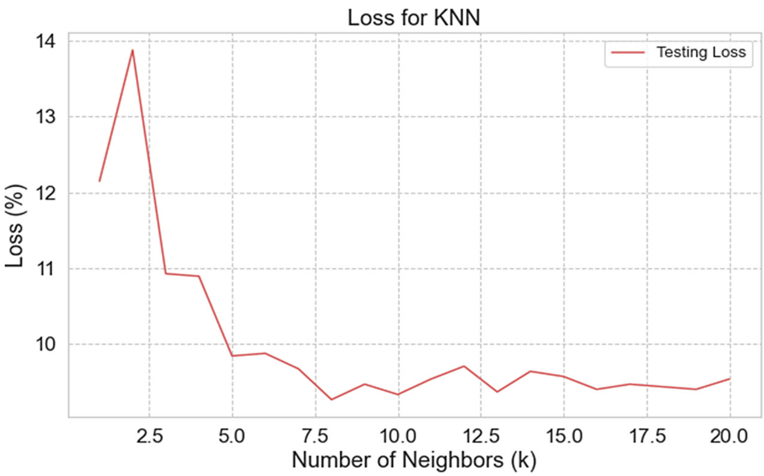

Fig. 4. The testing loss curve for the KNN algorithm.

Figure 5 shows the confusion matrix of the KNN algorithm, it detects data of 489, 426, 321, 400, 495, and 535 as true positives for the six activities: Walking, Laying, Downstairs, Upstairs, Sitting, and Standing. Figure 6 shows the normalized confusion matrix obtained from the KNN algorithm. It predicts a predicted label that is compared to the true label for the test dataset. The diagonal values of the matrix indicate the accuracy of the classification, while the values above and below the diagonal illustrate errors that occurred. Here, the normalized confusion matrix detects true positives of 0.99, 0.90, 0.76, 0.81, 0.93, and 1.0 for the six activities: Walking, Laying, Downstairs, Upstairs, Sitting, and Standing, respectively.

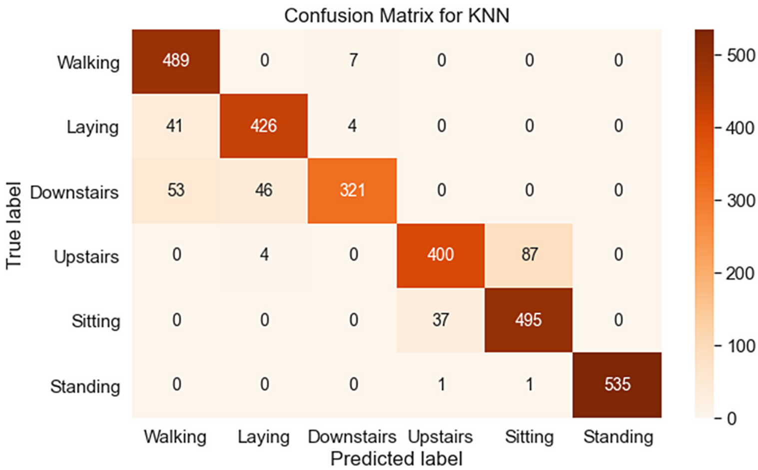

Fig. 5. The confusion matrix for the KNN algorithm.

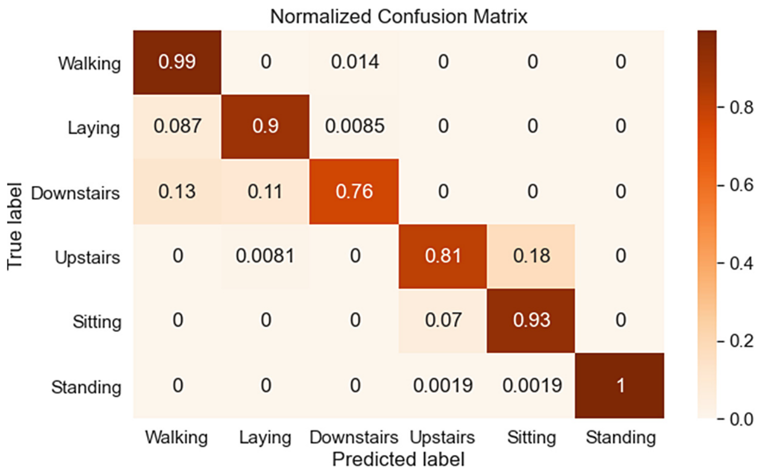

Fig. 6. The normalized confusion matrix for the KNN algorithm.

Table 1 demonstrates a classification report of the human activities with evaluation metrics in terms of the precision, recall, and F1-score of the KNN algorithm, to evaluate its relative performance for the used dataset. In this report, for the Walking class, 83.88%, 98.59%, and 90.64% for the precision, recall, and f1-score, respectively. For the Laying class, 89.50%, 90.45%, and 89.97% for the precision, recall, and f1-score, respectively. For the Downstairs class, 96.69%, 76.34%, and 85.37% for the precision, recall, and f1-score, respectively. For the Upstairs class, 91.32%, 81.47%, and 86.11% for the precision, recall, and f1-score, respectively. The precisions of Sitting and Standing classes are 84.91% and 1.00%, respectively, while the recalls are 93.05% and 99.663%, respectively, and the f1-scores, are 88.79% and 99.81%, respectively. Therefore, the macro average precision, recall, and f1-score are 91.05%, 89.93%, 90.12%, respectively.

Table 1. Classification report of human activities for the KNN algorithm.

Activity	Precision	Recall	F1-score	Support
Walking	0.8388	0.9859	0.9064	496
Laying	0.8950	0.9045	0.8997	471
Downstairs	0.9669	0.7643	0.8537	420
Upstairs	0.9132	0.8147	0.8611	491
Sitting	0.8491	0.9305	0.8879	532
Standing	1.0000	0.9963	0.9981	537
Accuracy	–	–	0.9046	2947
Macro average	0.9105	0.8993	0.9012	2947
Weighted average	0.9096	0.9046	0.9037	2947

Figure 7 illustrates the precision-recall curves for the KNN algorithm for each activity. Walking “class 1”, Laying “class 2”, Downstairs “class 3”, Upstairs “class 4”, Sitting “class 5”, and Standing “class 6” achieve area values of 0.989, 0.955, 0.956, 0.942, 0.945, and 1.000, respectively. Therefore, the area under the micro-average precision-recall curve is 0.965. Figure 8 demonstrates the ROC curves per class for the KNN algorithm. In this Figure, the highest values are the Walking class “class 1”, and the Standing class “class 6”, which achieve 1.00 area, also, this algorithm have 0.99 areas for Laying class “class 2” and Downstairs class “class 3”, Upstairs class “class 4”, and Sitting class “class 5”, respectively. In this Figure, the micro-average area for the ROC curve is 0.99.

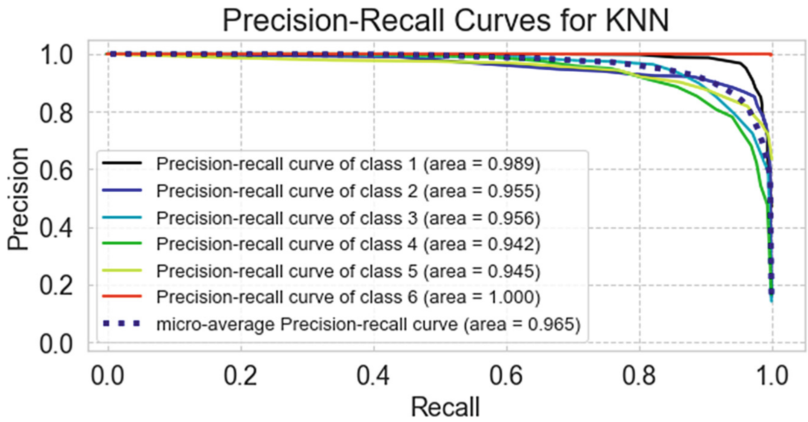

Fig. 7. Precision-recall curves for the KNN algorithm.

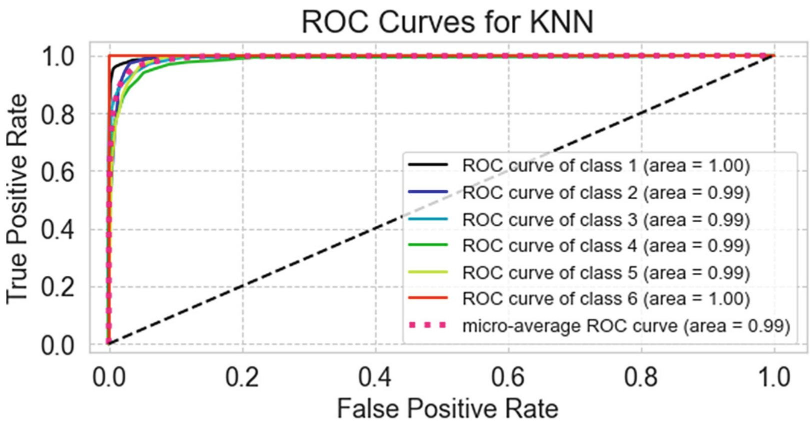

Fig. 8. ROC curves for the KNN algorithm.

Figure 9 illustrates a sample of the acceleration data over time collected from one person. In this Figure, three acceleration signals “raws” “ax, ay, and az” as functions in terms of the gravity acceleration (g) are shown. The blue raw represents the acceleration in the x- direction ax, while the green and orange raws represent the ay, and az which are the accelerations in the y- and z- directions, respectively. These signals are observed for 22000 s. The signals have an amplitude range roughly from -1 g to $+ 1$ g.

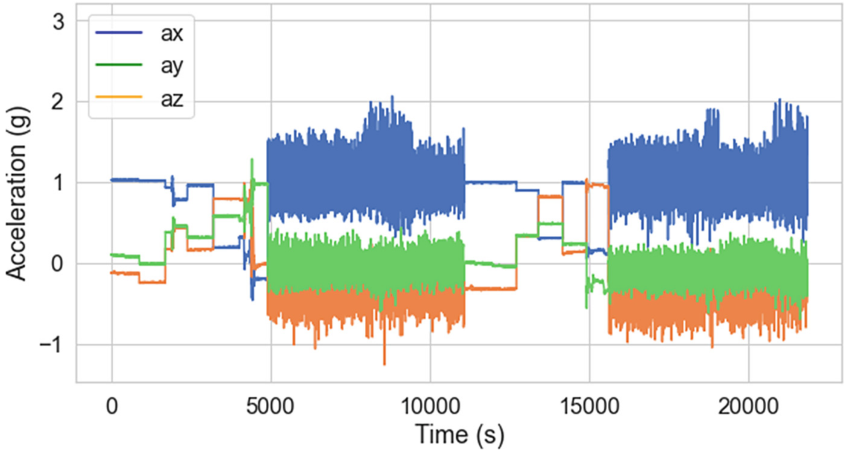

Fig. 9. A sample of the acceleration detected for one person.

4 Discussion

The results show that the proposed KNN algorithm has high performance of the testing loss and accuracy. In particular, Figs. 4 and 5 show low loss rate of 9.54% and high accuracy rate of 91.46% for the algorithm. The performance of the results depends on the optimal configuration of neighbor's number (*k*) for the KNN algorithm. When the *k* was set to 4, the algorithm reached a testing accuracy of 89.1% and when the *k* was changed to 10, the algorithm testing accuracy reached 90.66%. However, when the *k* was set to be 20, it achieves the high accuracy of 91.46%. Thus, one can argue that the parameter *k* is a significant variable to improve the performance of the algorithm. In the other hand, the micro-average area under the ROC curves of 99% was achieved, which means a high performance of the activity's classification for this algorithm. Additionally, the KNN is an algorithm suitable for classification multi-classes. So, it is performing better than other machine learning algorithms due to it was applied to many classes (six classes in this work). Table 2 illustrates the achieved accuracy compared by previous

Table 2. A comparison of the accuracy between the proposed algorithm and previous work.

Reference	Algorithm	Accuracy (%)
[11]	RF	83.59
[12]	J48	89.6
[13]	DT	73.72
[14]	NB	79
[16]	DT	84
Proposed algorithm	**KNN**	**90.46**

published works. From the comparison reported in this Table, it is shown that the KNN has highest accuracy.

5 Conclusion

This paper has reported on the implementation of a KNN machine learning algorithm for recognition of daily human activities. This algorithm achieves a testing accuracy of 90.46% and a testing loss rate of 9.54%. Experiments conducted to test the average precision of the proposed KNN algorithm, which reached 91.05%. Also, achieved average recall of 89.93% and average F1-score of 90.12%. The algorithm has an area under the micro-average precision-recall curve of 96.5%, while the mean area under the ROC curves is 99%. The normalized confusion matrix is presented to evaluate the algorithm's performance. With the optimal selection of the neighbors *k*, which is 20, a high performance is achieved for this algorithm. Moreover, we conclude that optimal setting of *k* parameter enhances the results. Therefore, referring to Industry 4.0, the KNN algorithm can accurately identify human activities in a smart factory environment. In the future, a graphics processing unit (GPU) environment can be utilized to train the proposed algorithm with larger datasets and increase the algorithm performance.

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References

1. Moktadir, M.A., Ali, S.M., Kusi-Sarpong, S., Shaikh, M.A.: Assessing challenges for implementing Industry 4.0: implications for process safety and environmental protection. Process Safety Environ. Protect. 1–12 (2018)
2. Ling, C., Xiaoze, L., Liangying, P., Menghan, W.: Deep learning based multimodal complex human activity recognition using wearable devices. Appl. Intell. 1–14 (2020)
3. Hsu, Y., Chang, H., Chiu, Y.: Wearable sport activity classification based on deep convolutional neural network. IEEE Access **7**, 170199–170212 (2019)
4. Stisen, A., et al.: smart devices are different: assessing and mitigating mobile sensing heterogeneities for activity recognition. In: The Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems, Seoul, South Korea (2015)
5. Ronao, C.A., Cho, S.-B.: Deep convolutional neural networks for human activity recognition with smartphone sensors. In: Arik, S., Huang, T., Lai, W.K., Liu, Q. (eds.) ICONIP 2015. LNCS, vol. 9492, pp. 46–53. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-26561-2_6
6. Bulling, A., Blanke, U., Schiele, B.: A tutorial on human activity recognition using body-worn inertial sensors. J. ACM Comput. Surv. **46**(3) (2014). Article 33
7. Aiguo, W., Guilin, C., Jing, Y., Shenghui, Z., Chih-Yung, C.: A Comparative study human activity recognition using inertial sensors in a smartphone. IEEE Sens. J. **16**(11), 4566–4578 (2006)

8. Lattanzi, E., Freschi, V.: Evaluation of human standing balance using wearable inertial sensors: a machine learning approach. Eng. Appl. Artif. Intell. **94**, 103812 (2020)
9. Wang, J., Chen, Y., Hao, S., Peng, X., Hu, L.: Deep learning for sensor-based activity recognition: a survey. Pattern Recogn. Lett. **119**, 3–11 (2019)
10. Hong, J., Ramos, J., Dey, A.K.: Toward personalized activity recognition systems with a semipopulation approach. IEEE Trans. Hum. Mach. Syst. **46**(1), 101–112 (2016)
11. Igual, R., Medrano, C., Plaza, I.: A comparison of public datasets for acceleration-based fall detection. Med. Eng. Phys. **37**(9), 870–878 (2015)
12. Chen, Y.F., Shen, C.: Performance analysis of smartphone-sensor behavior for human activity recognition. IEEE Access **5**, 3095–3110 (2017)
13. Fen, M., Yi, H., Liu, J., Li. Y., Ayoola, I.: Identifying typical physical activity on smartphone with varying positions and orientations. BioMed. Eng. OnLine (2015)
14. Ling, Y., Wang, H.: Unsupervised human activity segmentation applying smartphone sensor for healthcare, pp. 1730–1734 (2015)
15. Girija, C., Matthew, W., Farnaz, A.: Smart Phone based data mining for human activity recognition. Elsevier, Proc. Comput. Sci. **46**, 1181–1187 (2015)
16. UCI-HAR dataset, available in the Kaggle repository. https://www.kaggle.com/drsaeedmohsen/ucihar-dataset
17. Bao, L., Intille, S.S.: Activity recognition from user-annotated acceleration data. In: Ferscha, A., Mattern, F. (eds.) Pervasive Computing. Pervasive 2004. LNCS, vol. 3001, pp. 1–17. Springer, Heidelberg (2004). https://doi.org/10.1007/978-3-540-24646-6_1

Development of Correction Factors for FDM 3D Printers: Experimental Investigation and ANN Modelling

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Abstract. While additive manufacturing is already applied in industry in different varieties, even simple and widespread techniques such as the fused filament fabrication (FFF) process are still not fully understood in terms of influence of printing parameters or part orientation on the quality of fabricated parts. A main issue for using FFF in a reliable manner is the dimensional control of printed parts in comparison to the initially planned model. In this study the influence of printing parameters, part positioning on the printing platform as well as the use of different printer models has been evaluated in order to find correction factors for an optimised FFF process for high precision parts. The investigation has been carried out with two common printing materials (ABS and PLA) and printing tests have been conducted on two different FFF printers to evaluate the influence of hardware differences. Examination of the gathered data showed a substantial scattering of measured results, making the application of correction factors difficult, but not impossible. In addition, to predict the outcome of future prints a modelling approach using an artificial neural network (ANN) algorithm is presented. The developed ANN model paves the way for identifying a processing window, 3D printing parameters and correction factors for an optimised FFF process for high precision printed parts.

Keywords: Additive manufacturing · Process control · Parameter optimisation · Dimensional accuracy · ANN modelling

1 Introduction

Generative manufacturing techniques, also known as additive manufacturing (AM) or 3D printing, have seen a dramatic increase in industrial implementation over the last years. While the general principles and processes have been used for a long period within

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a smaller community, recent advances have made additive manufacturing techniques highly attractive for the efficient, cost-effective production of small up to medium batches [1, 2] and especially for customized products. However, the overall quality of the products is in many cases still not up to par compared to traditionally produced parts [3]. This especially accounts for the overall dimensions and tolerances of printed parts. This invokes the necessity of post-production steps, which is often counteracting the idea of implementing an additive process in the first place. This issue is even more challenging since a variety of different additive manufacturing technologies exist today, which differ in their physical principals, useable materials and the form and state of the material [4]. These differences also imply variances in the final outcome and properties of the produced parts (printing time, mechanical properties, surface roughness, precision and achievable dimensional accuracy) [5].

For the investigations in this work the most widely spread additive manufacturing technique was chosen, namely Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF), which belongs to the category of material extrusion [6]. In FFF, thermoplastic material is deposited on the build platform by melting a strand/filament of solid polymer within a heated print head and extruding the molten material through a nozzle with a thin (typically 0.4 mm) circular opening. As soon as the material is contacting the platform or a previously generated layer it solidifies and thereby forms the desired shape.

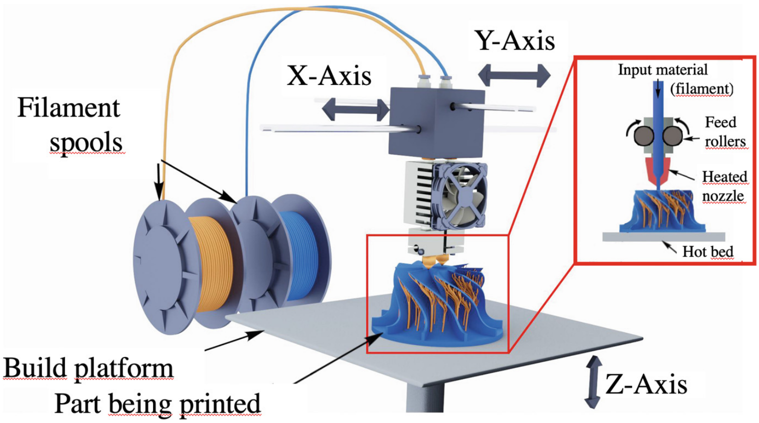

Fig. 1. Schematic description of FFF process [7]

By either moving the print head or the platform in z-direction the model is then subsequently built layer by layer until the final shape is reached. Complex geometries require additional material to support overhangs or even freestanding features (Fig. 1). Due to its cost-effectiveness, relatively low build times and overall flexibility (material/available printers/building volume), FFF has become one of the most popular of all AM techniques, being used in research, industry as well as the hobbyist area [8].

Previous work has determined strong dependencies of the print quality on finding optimal printing parameters [4]. Special focus was also given to the achievable mechanical properties and surface quality [9]. Objects manufactured with FFF showed disadvantages in comparison to parts that are traditionally manufactured such as by milling or molding [10]. In terms of dimensional accuracy, several investigations on the effect of different parameters have already been carried out. It could be shown that the deposition orientation, layer thickness as well as material shrinkage have a substantial impact on the accuracy of the manufactured part [11]. The latter can be addressed by carefully adjusting the printing chamber temperature, layer thickness and layer numbers [12, 13].

In this context, the aim of this work is to investigate the possibility to apply correction factors relying on a fixed set of printing parameters, material type and printer in order to achieve more accurate parts built by FFF. This is the first step to actively controlling the print with more sophisticated methods, ultimately resulting in an in-line printing control with the ability to react on changes in print quality in real time and optimizing printing parameters accordingly. Therefore, two different FFF printers and materials were chosen to print samples especially designed for determining the accuracy of different features in this study. The influence of position on the platform was also taken into account as a potential factor influencing the geometry.

2 Experimental Setup

2.1 Printing Setup

For the printing tests, two FFF printers were used to investigate possible variances between different manufacturers. In case of this work a dual-head printer from Leapfrog (Model “Bolt” [14]) and a zMorph 2.0 SX [15] were used (Fig. 2). Both printers are capable of printing both build and support material, with the zMorph being a rather special machine with interchangeable tool-heads.

Both printers work with a variety of materials (ABS, PLA, PVA, TPE, filled thermoplastics…) and commercially available software. While the g-code for the Bolt can be generated from the STL-file with widely spread slicers like Simplify3D or Cura [16, 17], the zMorph uses its own proprietary slicing software “Voxelizer” [18], which transform the triangulated surfaces described in the STL into voxels. This enables the software to generate different settings for each voxel and thereby print, for example, graded parts.

For all printing tests the two most common materials in FFF printing were chosen, namely ABS and PLA.

Since there can be great differences in the exact composition of the polymers, the brand and type of ABS/PLA was kept constant throughout all experiments. Similarly, the printing parameters were fixed based on preliminary tests. An overview of the most important printing parameters is given in Table 1.

The test geometry (Sect. 2.2) was printed five times within each printing cycle, four specimens being placed on the outmost possible corners of the printing platform and one in the middle. This was done to investigate the effect of different part placements on the platform. Since both printers feature different platform sizes, the spacing between the individual parts is different between the Bolt and the zMorph (Fig. 3).

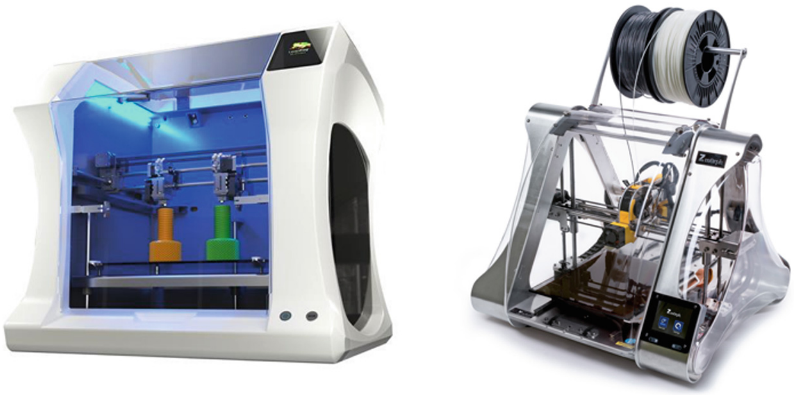

Fig. 2. FFF printers used; Leapfrog Bolt (left) and zMorph 2.0 SX (right)

Table 1. Overview of printing parameters

Parameter	ABS	PLA
T (Print/Bed) [°C]	220/100	200/60
Print Speed [mm/s]	60	60
Layer height [µm]	200	200
Infill [%]	30	30
Bottom/Top Layers	5/5	5/5
Outline shells	3	3

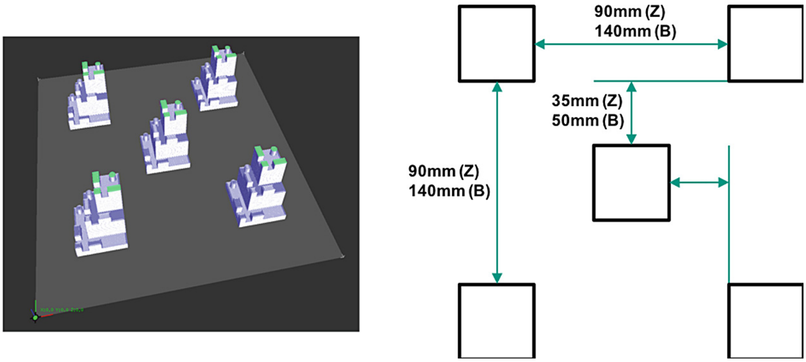

Fig. 3. Positioning of test specimen on print platform of Bolt (B) and zMorph (Z)

2.2 Test Structure

For an in-depth analysis of the dimensions a specific structure was created, that included a number of features enabling measurements in all three axes as well as roundness. The final test structure is shown in Fig. 4 and is derived from a number of preliminary models that were created but proved to be not convenient enough.

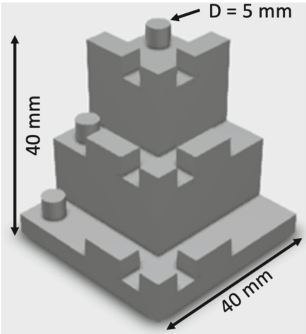

Fig. 4. Illustration of test structure

The basic structure has three levels, all of them being equipped with two cuboids, one cube and one cylinder. This allows for measurements of positive (solid) as well as negative (hollow) structures on different heights. In addition, the dimension of the different bases (40 × 40 mm, 30 × 30 mm, 20 × 20 mm) and the overall height allow for measurements of X/Y/Z accuracy of the print. The small cylinders on each base level make it possible to analyse the effect of the z position on the shape accuracy. In combination with the preliminary set printing parameters the printing time of five specimens slightly exceeded eight hours.

Each test was carried out three times. All obtained specimens were measured and taken into account accordingly to ensure a statistical conformity.

2.3 Characterisation

Printed specimens were measured using an optical coordinate measurement system from Werth Messtechnik GmbH (Video-Check-IP). The system is capable of highly precise 3D measurements of distances, diameters and heights and therefore ideally suited for the structure in demand. The system automatically regulates the amount of illumination depending on the examined area of the test structure and is able to reach a resolution of up to 0.5 μm. The measurement uncertainty is depending on the measured length (L) and can be calculated as follows:

$$E_1 = \left(2.5 + \frac{L}{200}\right)\mu\text{m} \quad (1)$$

To ensure repeatability the measuring equipment is mounted on a hard stone (granite) table, pedestal and other structural parts are also executed in a stiff manner.

Figure 5 shows the measurement plan carried out on each printed sample. On each level X-Y dimensions, X-Y gaps, and diameters of the cylindrical features were measured as well as distances between the different levels in Z-direction.

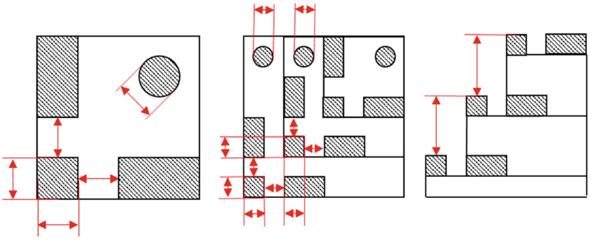

Fig. 5. Measurements carried out on test specimen

Dimensional error was calculated based on the ideal value, derived from the original CAD drawing, which can be considered as the target (Reference) value. The relative dimensional error was calculated as follows:

$$error\% = \frac{measured\ value - ideal\ value}{ideal\ value} * 100\% \quad (2)$$

3 Results and Discussion

3.1 Results for ABS Material

Figure 6 shows the measurements of solid structures in X and Y-direction for specimen printed in ABS. It can be seen that the overall dimensional error is in the range between −1% to 3% and the deviations in the measured values is relatively high for certain values, which makes hard to give a solid interpretation of the data. However, it is clearly visible that the measured values are most of the time bigger than the expected values derived from the CAD file. This is mainly due to the influence of the path width, which causes the solid parts to be bigger. Looking at the individual segments of the test structures it can be seen that the bottom segment has the best accordance to the target values, with a maximum dimensional error of less than 1%. This is mainly due to the positive influence of the heated platform, which allows for a slower and more homogenous cooling of the material.

When comparing the X- and Y-direction measurements two points become obvious: a) the general tendencies implied by the positioning of the specimen on the platform are the same and b) dimensional error in X is slightly lower than in Y.

Consequently, measurements of hollow structures/gaps showed a negative dimensional error, resulting from the slightly increased size of the elevated features. The general error is slightly larger than in the solid structures as it is exemplarily shown in Fig. 7, which shows the dimensional error of gaps in x direction.

The height measurements for evaluating the z-Axis accuracy were carried out by measuring two distances, as shown previously in Fig. 5. The data (see Fig. 8) shows only a small dimensional error of up to −2% for the distance between segment 1 and 2 and even lower values of less than −1% for the upper distance. The difference can be explained by the thermal shrinkage of the material, which is relatively large for ABS.

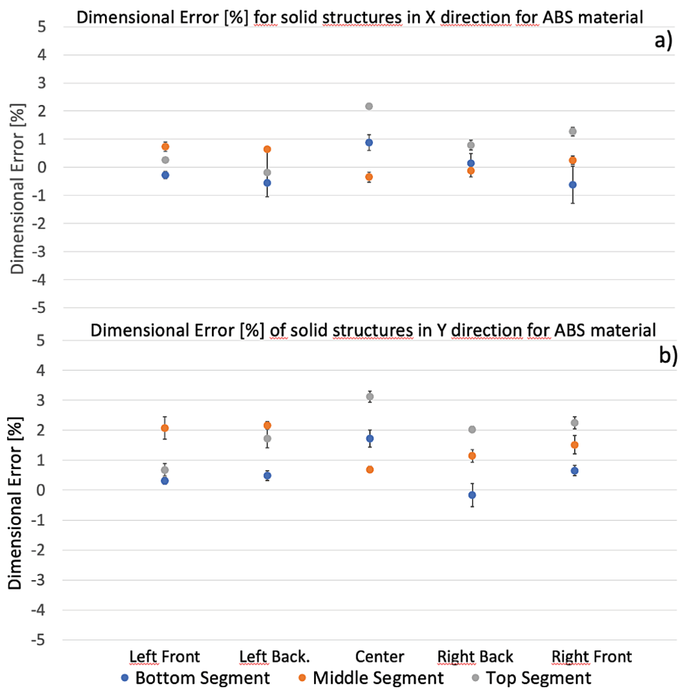

Fig. 6. Dimensional error of solid parts in a) X and b) Y direction for ABS

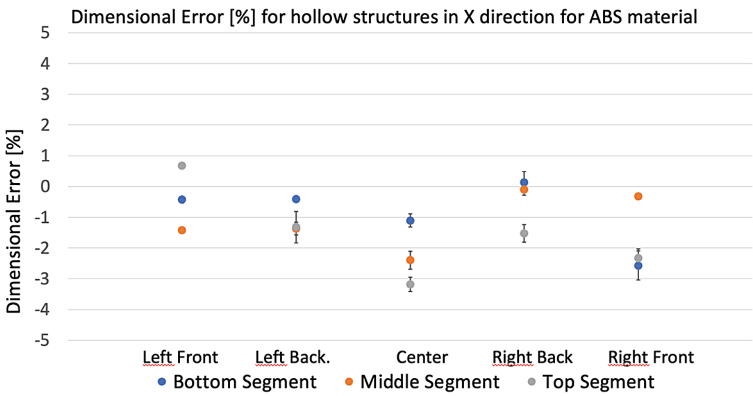

Fig. 7. Dimensional error of hollow parts in X direction

Therefore, it can be concluded that the dimensional accuracy in z-direction is of a surprising degree without having to introduce a correction factor, although it is also obvious that individual errors, as represented in the scattered values around the median, are still a problem to be addressed.

In conclusion, the measurement results indicate that corrective factors for the ABS material is a must and can be introduced for certain printing directions, while others,

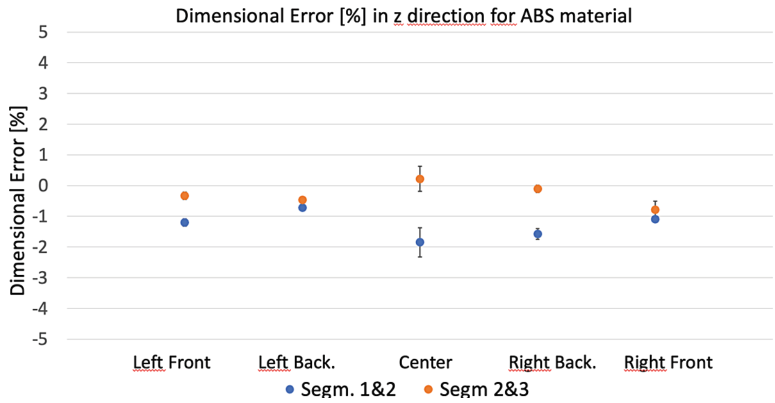

Fig. 8. Dimensional error in Z direction

for example the z direction, already show a good accuracy only lacking a proper control system to improve the repeatability and lower the scattering within the individual prints.

3.2 Results for PLA Material

Structures printed in PLA exhibited similar behaviour to those printed in ABS. As an example, the results of measurements along the X-Y direction of the solid parts are shown in Fig. 9.

It can be seen that the general trends for the individual positions on the print platform are comparable and the dimensional error is in a similar scale, albeit slightly higher than the values experienced using ABS. One would expect the values to be smaller than in ABS since the thermal shrinkage of PLA is lower than the one of ABS, but the complicated interplay of material and process parameters denies such a simple explanation.

In Z-direction PLA exhibits a slightly better accuracy than ABS. This may be the result of the lower thermal shrinkage, as the z-axis is affected more by this property. Again, due to the small dimensional error no corrective factor can be applied that increases the accuracy for PLA as well.

3.3 Comparison of Printers

On the Leapfrog Bolt the exact same structures were built and measured as previously shown for the zMorph. Dimensional accuracy in X and Y direction are comparable, ranging from -1.5% to 4% for solid structures and from -5% to 2% for hollow structures, valid for both materials. This is slightly less accurate than the prints using the zMorph printer, which basically is down to the accuracy of the linear axis, which is stated to be better on the zMorph. In Z direction, the Bolt produces better results than the zMorph, lowering the possible dimensional error to almost zero, but again with the values showing a wide variety around the median. Therefore, although the Bolt produces a slightly better result in Z direction, again no corrective value can be applied but an improvement in the dimensional accuracy can only be achieved by implementing a suitable control strategy.

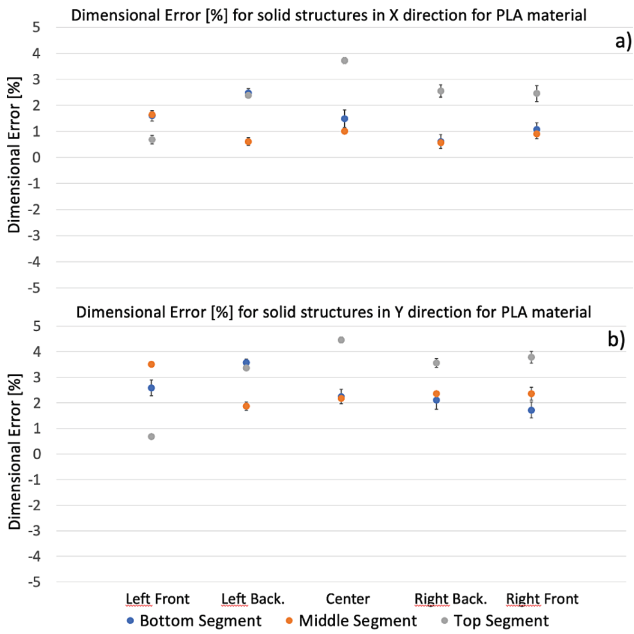

Fig. 9. Dimensional error in a) x- and b) y-direction of solid parts for PLA

As it can be seen from the results for both printers the measurements for both ABS and PLA showed a relatively high scattering of the values. However, the general tendencies can be used as a basis for a first corrective adjustment of the dimensions of the CAD files. Table 2 shows the relative correction factors based on the findings of this work that can be applied to the CAD model to increase the dimensional accuracy of the final part. These factors are derived from the dimensional errors described earlier, taking into account only the most reliable sets of data gathered in the experiments. For some directions, no clear recommendations can be given, as the results in the experiments indicate no common value for compensation. In general, these values mainly account for compensating the material shrinkage, the inaccuracies due to the fixed width of the extruded path and, to a minor extent, the inaccuracies of the overall mechanical setup of the printers.

Table 2. Corrective factors derived from the experiments

Axis	Material	
	ABS	PLA
X	N/A	+1,0%
Y	+1,50%	+2,50%
Z	N/A	N/A

3.4 Algorithm for Printing Fabrication Error Estimation

This section is devoted to design an Artificial Neural Network (ANN) to model the relationship between the input and output parameters based on the experimental results. ANN was utilised in this study due to its high ability to tackle complex non-linear problems, which are very difficult to solve using other techniques [19]. ANN can be implemented to solve classification/regression problems. Herein, the proposed ANN model works to estimate the error of 3D fabricated (printed) parts.

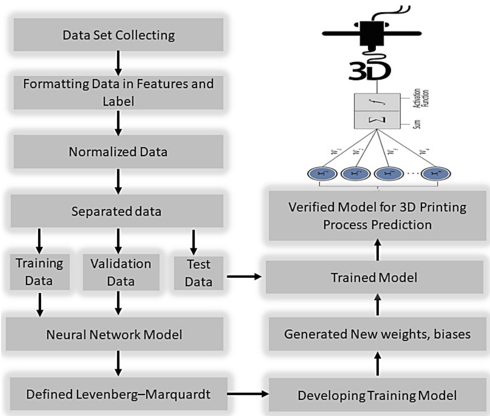

Fig. 10. Workflow of the ANN algorithm

The printed parts were assessed to collect necessary data sets. The data was separated for input (features) data as “Position, Z-Level, X/Y Axis, Soiled/Hollow/Diameter dimension and Short/Long length” and label (response) data as “Error%”.The ANN Algorithm works as follows, see Fig. 10. Input data and label data were stored into two matrixes 5 × 120 and 1 × 120, respectively. Then, the entire data sets were divided randomly into training data, validation data, and testing data. The proposed algorithm was developed using the Neural Network toolbox in MATLAB. Different ANN designs were tested and evaluated for the minimum error between the expected and estimated results. The proposed ANN was designed based on 5 neurons for input layer, 10 neurons for hidden layer and 1 neuron for the output layer as shown in Fig. 11. The Levenberg–Marquardt was selected as a neural network algorithm.

For the training phase of the ANN algorithm, random values for initializing weight and bias of neural network, 1000 epochs (training step) and 0.1 learning rate were set.

Further to the development of the training session, Fig. 11. The proposed training ANN model was updated with the newly generated weights and bias that minimize the training error in order to estimate the correct response “Errors%” of the 3D printed parts.

As shown in Fig. 12, the results of the training gradient was calculated to be 0.029498 at epoch 19 and the best validation results are at epoch 13 with a mean square error of 0.47826 as shown Fig. 13.

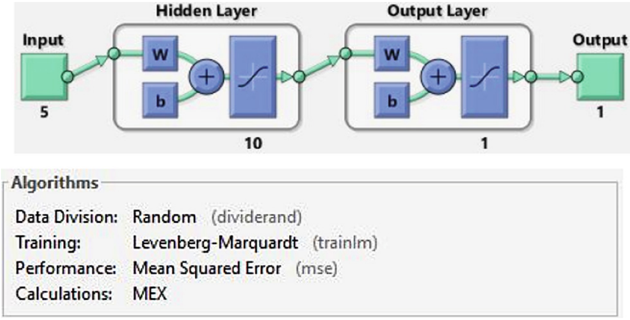

Fig. 11. Optimal structure of the proposed ANN

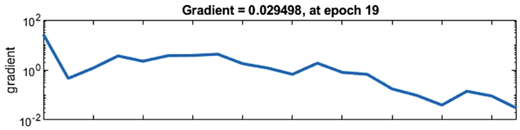

Fig. 12. Result of training gradient

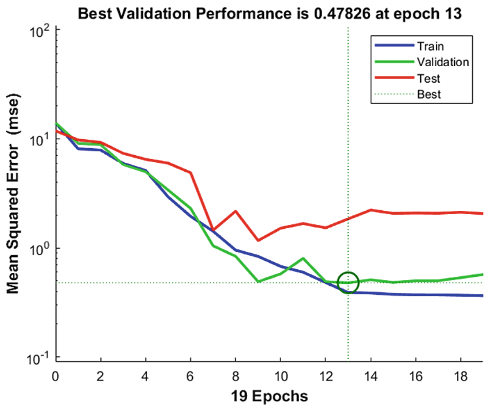

Fig. 13. Validation performance of neural network

Figure 14 shows the performance of the regression algorithm developed to predict the error of AM fabrication process using zMorph 3D printing. In particular, the proposed ANN model successfully estimates the error percentage in the 3D printed products for different input parameters i.e. position on bed, Z-level, X/Y axis, solid/hollow/diameter and short/long length of the product. This is clearly revealed considering the plotted data around the fit line in the training, validation and testing phases of the proposed ANN model.

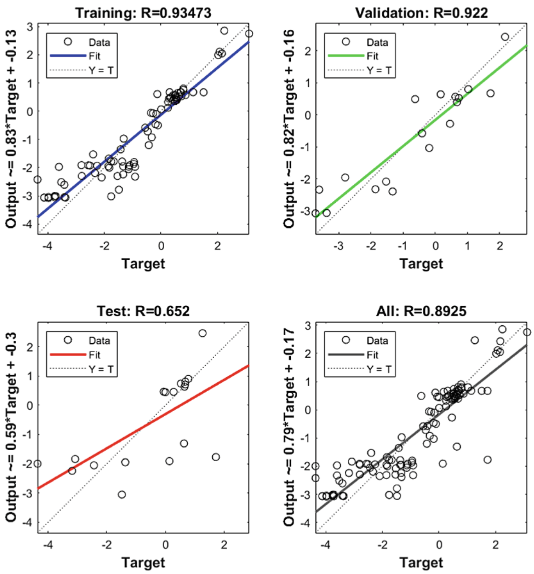

Fig. 14. Validation performance of neural network

4 Summary and Outlook

In this work correction factors for fused filament fabrication were established by developing a test structure and printing experiments especially designed for analysing the dimensional features of prints. Results showed that despite a certain scattering in the measured dimensions, correctional factors can be applied to enhance the dimensional accuracy of future prints.

Additionally, an ANN model was developed based on the experimental results of the dimensional error% of the printed parts for the range of examined input variables, making it possible to predict the outcome of prints in terms of dimensional accuracy.

Both approaches can help to increase the accuracy for even simple printing techniques such as FFF. As this a widely used technique and hugely popular among hobbyists as well as industry, the potential for reducing scrap and therefore material waste is enormous if printing accuracy can be improved without trial and error. Taking into account the currently available materials, which are mostly not or only under very specific conditions biodegradable, decreasing the number of failed prints and wasted polymers/resources can have a huge impact.

Further improvements can be made by implementing additional controllers, for example a PID-controller that implies a loop feedback mechanism to the movement of all individual axis. Future work should also consider a wider variety of materials, as the range of materials for fused filament printing is constantly extended. Finally, the suitability of the developed ANN model has to be verified for other printer models to prove the general applicability of such an approach. European Powder Metallurgy Association.

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References

1. Schmidt, T.: Potentialbewertung generativer Fertigungsverfahren für Leichtbauteile, Springer, Berlin/Heidelberg (2016)
2. Richard, H.A., Schramm, B., Zipsner, T.: Additive Fertigung von Bauteilen und Strukturen. Springer, Wiesbaden (2017)
3. Serin, G. et al.: A review of additive manufacturing. In: 17th International Conference on Machine Design and Production, 12–15 July 2016, Bursa, Turkey (2016)
4. Elkaseer, A., Müller, T., Charles, A., Scholz, S.: Digital detection and correction of errors in as-built parts: a step towards automated quality control of additive manufacturing. In: WCMNM 2018, Portorož, Slovenia, pp. 389–392 (2018)
5. Gibson, I., Rosen, D., Stucker, B.: Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping and Direct Digital Manufacturing. Springer, New York (2015)
6. Galantucci, L.M., Bodi, I., Kacani, J., Lavecchia, F.: Analysis of dimensional performance for a 3D open-source printer based on fused deposition modeling technique. Proc. CIRP **28**, 82–87 (2015)
7. Elkaseer, A., Schneider, S., Scholz, S.G.: Experiment-based process modeling and optimization for high-quality and resource-efficient FFF 3D printing. Appl. Sci. **10**, 2899 (2020). https://doi.org/10.3390/app10082899
8. Rieker, S. et al.: 3D printing of metal parts by means of fused filament fabrication - a non beam-based approach. In: Euro PM 2017 Congress & Exhibition. Proceedings: 1–5 October p. 6 (2017). ISBN:978–1–899072–49
9. Mohamed, O.A., Masood, S., Bhowmik, J.L.: Optimization of fused deposition modelling process parameters: a review of current research and future prospects. Adv. Manuf. **3**(1), 42–53 (2015)
10. Lieneke, T., Denzer, V., Adam, G.A.O., Zimmer, D.: Dimensional tolerances in additive manufacturing: experimental investigation for fused deposition modeling. Proc. CIRP **43**, 286–291 (2016)
11. Nancharaiah, T., Ranga, R.D., Ramachandra, V., Raju, R.: An experimental investigation on surface quality and dimensional accuracy of FDM components. Int. J. Emerg. Technol. **1**(2), 106–111 (2010)
12. Wang, T.M., Xi, J.T., Jin, Y.: A model research for prototype warp deformation in the FDM process. Int. J. Adv. Manuf. Technol. **33**(11–12), 1087–1096 (2007)
13. Panda, B.N., Shankhwar, K., Garg, A., Jian, Z.: Performance evaluation of warping characteristic of fused deposition modelling. Int. J. Adv. Manuf. Technol. **88**(5–8), 1799–1811 (2017)
14. Leapfrog Bolt. https://www.lpfrg.com/products/leapfrog-bolt-pro/
15. zMorph SX 2.0 Knowledge Base. https://support.zmorph3d.com/hc/en-us/categories/201196109-ZMorph-2-0-SX
16. Simplify 3D Slicing software. https://www.simplify3d.com/
17. Ultimaker Cura Slicing software. https://ultimaker.com/de/software/ultimaker-cura
18. zMorph Voxelizer Slicing Software. https://voxelizer.com/
19. LeCun, Y., Bengio, Y., Hinton, G.: Deep learning. Nature **521**, 436–444 (2015)

An Integrated Framework for Reactive Production Scheduling and Inventory Management

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Abstract. Industry 4.0 promises sustainable and more efficient manufacturing through new digital technologies. However, existing methodologies like Lean Manufacturing have been tested and proven, and could benefit greatly from increased digitalisation. In this paper, we claim that the enhancement of existing Lean and related methodologies with digital technology is a necessary step to fulfil Industry 4.0's promise. To demonstrate this claim, we introduce a framework for integrating raw material and finished product inventories and production scheduling. We validate the framework by developing a proof-of-concept system that combines constraint programming (CP) and inventory management to address a combined reactive scheduling and inventory management problem. The production model we use is a Resource-Constrained Project Scheduling Problem (RCPSP) with three finished products and four raw materials, and the two-bin or (s, Q) inventory policy. The system enables coordination of raw material, finished product and work-in-progress inventories through optimal scheduling (minimal makespan). The results inform operators of expected stock-outs and consumption and production rates, while allowing for modifications in case of disruption.

Keywords: Inventory management · Manufacturing · Optimisation · Production scheduling · Constraint programming

1 Introduction

Industry 4.0 is a solution for increasing the sustainability of current manufacturing practices, as well as addressing challenges like the rise of electronic commerce, emerging technologies and quick changes in the geopolitical landscape that disrupt traditional supply chains. *Industry 4.0* is the term commonly used to refer to fourth industrial revolution and the digital transformation of the business world. On one hand, Industry 4.0 builds upon the combination of physical and digital systems (or *cyber-physical systems*) and the use of new digital technologies such as Artificial Intelligence (AI) and Machine Learning (ML) to improve manufacturing workflows and outcomes. On the other hand, there exist many established and proven methodologies like Lean Manufacturing (LM),

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Six Sigma (SS) and Statistical Process Control (SPC). Enhancing the latter by digitalisation and other IT tools has been widely discussed (e.g., in Buer et al. [3] and Rosin et al. [14]). However, it has been noted that smaller enterprises will suffer because of the high investments needed, and the increased flexibility introduced by Industry 4.0 will allow bigger enterprises to steal market share for customised products, a market segment now usually dominated by small and medium-sized enterprises (SMEs) [15]. In our experience, SMEs are not enhancing and integrating tested-and-proven LM methodologies with new technologies, but rather these are being forgotten or eschewed because of the increasing popularity of fashionable AI/ML tools and terms.

We claim that the strengthening of existing LM and related methodologies with new technologies offers a more solid foundation to the realisation of Industry 4.0 objectives. In this paper, we propose a combination of newer (CP) and existing (inventory management) technologies to address a combined reactive scheduling (i.e., when schedules are adjusted in response to real-time events) and inventory management problem under uncertainty to illustrate the effectiveness of this claim. We believe that this approach will eventually lead to the revitalisation of SME-focused research in LM, SS and SPC techniques by merging them with digital technologies, instead of simply "automating Lean". Most importantly, it will lead to increased sustainability of manufacturing operations by rationalising the use of resources in real time.

1.1 Previous Work

Inventory and production scheduling are both crucial in a manufacturing environment: inventory management controls storage and replenishment of raw materials and products, whereas scheduling enables the effective allocation of manufacturing tasks and resources. Optimisation models that combine both have given priority to the scheduling problem due to its complexity. For example, Yin et al. [19] presented a dynamic programming model of a production and inventory system of steel coils, with just-in-time (JIT) operation. A decision maker develops a schedule that meets the requirements of two agents. Cheng et al. [4] analysed the model of an integrated production-inventory-distribution system with batch-processing machines and arbitrary-size jobs. The objective is to minimise the total cost, including production and inventory. A similar integrated approach was presented by Lee and Yoon [9], where the objective is to find the coordinated schedule of production and delivery that minimises the total cost of the associated work-in-progress (WIP) inventory, finished product inventory and delivery, and is solved using heuristics. Fumero and Versellis [5] proposed a model to coordinate capacity management, inventory allocation and vehicle routing, and solved it using Lagrangian relaxation. Gunn et al. [8] optimised daily, weekly and monthly production plans for a dairy company, so as to support the inventory function. Luo et al. [10] presented a divergent production scheduling problem, that is, a system where many finished products are made from a few raw materials, with coupled inventories. The problem is formulated as an integer program and solved using particle swarm optimisation.

The literature is scarcer for systems that consider reactive scheduling and inventory control simultaneously. Takeda Berger et al. [18] proposed a conceptual model for a data-driven predictive-reactive scheduling and inventory system that combines ML and simulation. They noted the existing gap in research between disruptions on the shop floor and their effect on inventories, albeit no experimental results or concrete methodologies beyond simulation are proposed. Relvas et al. [13] proposed a similar approach for a refinery in Portugal. While highlighting that the research gap in reactive scheduling and inventory management exists in the process industries as well, they introduced a linear programming model where six types of perturbations can trigger a re-schedule, with the objective of minimising the difference between the total amount of products transported by the pipeline and the total amount of outputs to clients. Revision plans were assessed, and it was found that model sizes decreased whenever the disruptions happened closer to the end of the time horizon. Gomes et al. [7] presented a reactive scheduling mixed-integer linear model for a flexible job-shop with an objective function that weighs in the amount of in-process inventory, but does not encompass the inventory of finished products.

This brief review demonstrates that most integrated scheduling-inventory systems either consider scheduling and inventory management of a single product, or present a monolithic solution approach to both problems, or consider inventories as accessory to distribution. In the present paper we propose a framework intended to simultaneously support inventories of raw materials and finished products, and is especially suitable for reactive production scheduling because it adapts to the changing conditions in the production floor. The framework is demonstrated via proof-of-concept by combining constraint programming (CP) and inventory management heuristics to address a combined reactive scheduling and inventory control problem, subject to disruptions.

2 A Framework to Integrate Scheduling and Inventories

Figure 1 is an extension of a production and inventory management concept proposed by Man et al. [11]. The first step of the production planning system is to do *Demand Management* (DM) of the finished products. In manufacturing, DM refers to forecasting and managing customer demand for order fulfilment purposes [17]. Forecasting is very important in industries that produce to stock, and less important in job-shops because of the greater uncertainty in make-to-order environments. Distribution planning is another important component of DM.

The next activity is *Capacity Planning*. This is the process of determining the production capacity needed by an organisation to meet changing demands for its products. First, a rough check (*Master Planning*) is made on the feasibility of the master schedule against labour availability, raw materials and limiting pieces of equipment, before the detailed *Material Requirement Planning* (MRP), where detailed calculations give an accurate image of the feasibility of the plan. Finally, short-range, operational scheduling and *Quality Control and Analysis* (QC/QA) define production. Scheduling is key

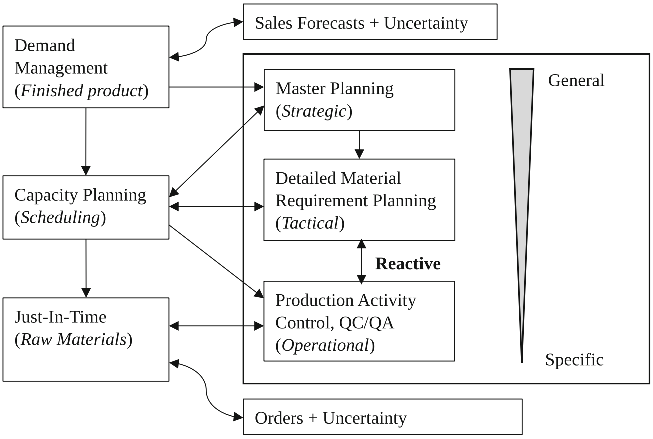


Fig. 1. A reactive production planning system that integrates demand management, capacity planning and inventory management. The arrows indicate information flows and the solid box represents production-related activities.

to find the optimal allocation of manufacturing tasks and resources to achieve certain optimisations (e.g., minimise makespan or costs). Scheduling is relatively simple in the process industries, but it needs more detail in job shops, batch flow and assembly. The schedule only *suggests* the sequence of jobs, as there are unforeseen events or decisions that require adjustments in real time. Finally, a raw material inventory system (e.g., a system based on *Just-in-Time*) will enable the company to oversee and manage inventories of raw materials and finished products.

We propose a framework for integrated, reactive scheduling and inventory management, and provide a proof-of-concept that combines CP and inventory management heuristics to deal with unforeseen disruptions. A schedule, calculated using the high-level modelling language MiniZinc[1] version 2.5.3, is used to guide inventory heuristics of finished products and raw materials, thus connecting product demand forecasts to raw material requirements and orders. The results allow manufacturing companies to rationalise resources while overseeing the whole system, thus increasing sustainability and taking uncertainty into account.

3 Inventory and Production Scheduling

We describe next the components of the framework that correspond to inventory and production scheduling.

[1] https://www.minizinc.org/software.html, accessed on 23 February 2021.

3.1 Inventory Management

Inventory models ensure that the right amount of materials is available for manufacturing and the right amount of products is available for order fulfilment. The inventory policy implemented in the proof-of-concept is the (s, Q) system, also known as the *two-bin* system [17]. In this policy, when the inventory level of a material drops to the reorder point s or below, a replenishment order of constant size Q is placed. In production, parameter Q is usually estimated as the Economic Order Quantity using average demand, and parameter s depends on the replenishment lead time L, i.e., the time between the placement of the order and the actual replenishment event according to $s = \hat{x}_L + k\sigma_L$, where $\hat{x}_L$ is the expected demand during L, k is a safety factor defined by the company (often $k = 1$), and σ_L is the standard deviation of the errors of the forecasts of total demand over L. The policy was implemented in R[2] version 4.0.3.

3.2 Scheduling and Constraint Programming

Scheduling problems emerge in situations where a number of activities has to be completed with a limited amount of resources and time, and a number of constraints must be satisfied [2]. By creating a planning component to decide the schedule of activities, an objective function could be optimised, e.g., minimising the total time to complete all activities [1] or effectively allocating resources in production. The most basic parameters of a scheduling model are tasks and resources. There also may be precedence constraints between tasks and consumption constraints on resources. Since scheduling is a combinatorial optimisation and constraint satisfaction problem, it can be modelled using CP. We use the MiniZinc modelling language where combinatorial optimisation problems can be expressed in a solver-independent way [12]. The base scheduling model of our proposed integrated framework is the *Resource-Constrained Project Scheduling Problem* (RCPSP), which is a widely used scheduling model in manufacturing environments. A key concept of RCPSP is the use of cumulative resources, which can run multiple jobs in parallel and are subject to a capacity constraints. The interested reader may refer to Schutt et al. [16], who explain RCPSP in detail.

4 Methodology

4.1 Problem Instance and Manufacturing Data

We consider a manufacturing problem where we have multiple cycles of demands of finished products. In the factory, there are a set of *renewable resources* R and a set of non-renewable resources or *materials* M ready to use for production, where a renewable resource is denoted by $r \in R$ and a material is denoted by $m \in M$. A certain amount of this resource r will be consumed at the beginning of a task, and r will be released at the end of the task. Some examples of renewable resources are machines, equipment, and human resources. A renewable resource r has a usage capacity of $cap[r]$, specifying how many usage units it can process in parallel at any given time, whereas the amount

[2] http://cran.r-project.org/, accessed on 23 February 2021.

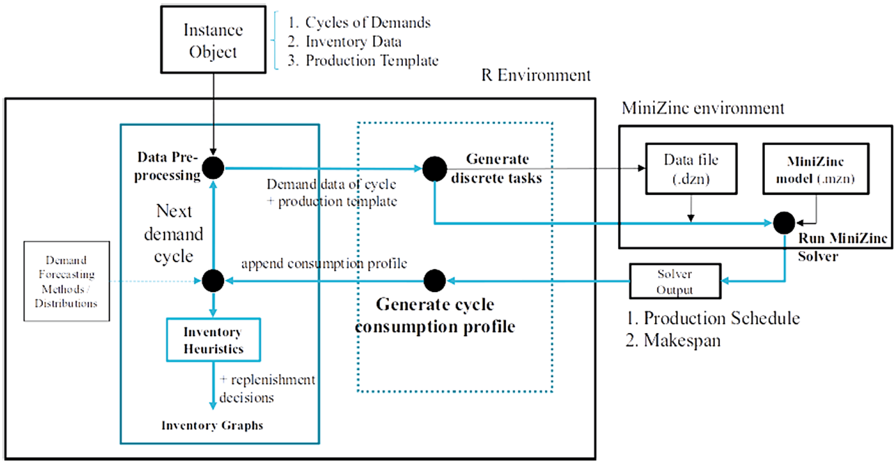


Fig. 2. Implementation of the integrated reactive scheduling and inventory system. MiniZinc is used to model the scheduling problem, while R is used to compile and process all flows of data, including the implementation of the inventory models.

of a material m may change after the completion of a task. A material can be a raw material, work-in-progress (WIP), or a finished product. A factory also has a set of manufacturing tasks T, where a task is denoted by $i \in T$. A task, also known as an activity or an event, will consume some renewable resource r given by $task\_res[r, i]$, and may increase or decrease the inventory levels of some material m by an amount $task\_mat[m, i]$. Given n_c cycles of demands of finished products, we want to know the optimal schedule for each cycle in order to determine the consumption of every material over the planning horizon, and see the coordinated variation between inventories of raw materials and finished products.

We define a *production template* as a blueprint of manufacturing operations to create a set of finished products. Tables 1, 2, 3 and 4 show some of the parameters used to run the proof-of-concept. After scheduling, the results representing inventory levels of materials and finished products is appended to the production template. An instance object of a production template contains these manufacturing data:

1. List of discrete manufacturing tasks that needs to be completed to produce one or more units of a finished product. E.g., to make a finished product A (FP_A), the tasks need to be completed are $Task_{A1}$, $Task_{A2}$, and $Task_{A3}$.
2. Duration of each task (dur). The total time to complete task i is given by $dur[i]$.
3. Precedence constraints between manufacturing tasks ($dcons$), which determines the time constraints between tasks. For example, the first line of the example on Table 4 expresses that the start time of $Task_{A1}$ must be at least 8 time units before the start time of $Task_{A2}$.
4. Consumption of renewable resources for every task ($task\_res$). A task i may occupy some renewable resources r for some amount of usage unit given by $task\_res[r, i]$.

Table 1. A multi-cycle demand data (in units) of three finished products (FP).

Cycle	FP_A	FP_B	FP_C
1	1	2	2
2	2	1	3
3	3	1	1
4	2	0	3
5	3	2	2

Table 2. Example of a $task\_mat$ template, describing how a task affects the inventory level (units) of each material (finished product A only).

Material	$Task_{A1}$	$Task_{A2}$	$Task_{A3}$
MAT1	-2	-3	-7
MAT2	-5	-2	-2
MAT3	-3	-4	-1
FP_A	0	0	+1

Table 3. Example of a $task\_res$ template, describing the usage consumption amount of a task for every renewable resource (finished product A only).

Res	$Task_{A1}$	$Task_{A2}$	$Task_{A3}$
MAC1	4	5	1
MAC2	2	0	8
MAC3	1	5	3

Table 4. Example of a $dcons$ template, describing the precedence constraints between tasks.

Task	diff	Task
A1	8	A2
A2	10	A3

5. Production/consumption activity of materials for every task ($task\_mat$). Each task i may produce (+) or consume ($-$) a certain unit of some material m (Table 2).
6. Demand of finished product for n_c number of cycles, as shown in Table 1. DM techniques may be used to estimate the demands.
7. Inventory parameters for every material m, e.g. current inventory level, reorder point s, safety stock SS, order-up-to-level S, carrying charge r, fixed cost A, variable cost v, and replenishment lead time L.

Figure 2 describes the implementation of the system. The instance data is preprocessed in R to generate discrete tasks according to the demand of each cycle and fed to MiniZinc. For every demand cycle, MiniZinc produces an optimal schedule in discrete and arbitrary time units. Scheduling is repeated for every demand cycle, and the schedules are combined to create a consumption profile of each material. This profile is used as the demand data for the inventory models, which suggest replenishment decisions as a function of material consumption. This allows coordination between scheduling and inventory while considering uncertainty.

4.2 Scheduling

The objective of the scheduling model is to minimise the makespan (t_{ms}), i.e., the total completion time subject to the following constraints:

1. Cumulative constraint. This constraint ensures that at any given time, the total usage of every renewable resource r does not exceed its usage capacity $cap[r]$:

$$\sum_{i \in T \,:\, start[i] \leq t < start[i] + dur[i]} task\_res[i] \leq cap[r], \qquad \forall t \in [0 \mathinner{..} t_{ms}], \quad \forall r \in R$$

2. Inventory constraint. This constraint ensures that at any given time, the total consumption of any material m does not exceed its maximum inventory level $max[m]$:

$$\sum_{i \in T \,:\, start[i] = t} task\_mat[m, i] \leq max[m], \qquad \forall t \in [0 \mathinner{..} t_{ms}], \quad \forall m \in M$$

3. Makespan constraint. This constraint ensures that all of the manufacturing tasks will be started and completed before the makespan t_{ms}: $start(i) + dur[i] \leq t_{ms}, \forall i \in T$.
4. Difference constraint. Describes generalised precedence relations between tasks. The constraints are specified in the problem instance as $dcons$ with columns Task i, t_{diff}, and Task j. These constraints take the form $start[i] + t_{\text{diff}} \leq start[i]$, $\forall (i, t_{\text{diff}}, j) \in dcons$, $t_{\text{diff}} \in [0 \mathinner{..} t_{ms}]$, $i, j \in T$.

MiniZinc produces a schedule represented as an array of starting times. An example of how a schedule is represented in an array is $[0, 11, 19, 0, 11, 19, 0, 11, 19, 0, 8, 0]$, meaning that Task 1 starts at $t = 0$, Task 2 starts at $t = 11$, etc. MiniZinc also produces the makespan value t_{ms}.

4.3 Consumption Profile Generation for Inventory Models

The scheduling process is executed as many times as the number of cycles n_c. Once every task in every cycle is scheduled, a consumption profile of each raw material and WIP, and a production profile of each finished product and WIP, can be generated. A consumption (production) profile tells how many units of material are being consumed (produced) at every moment. Consumption events will happen at the beginning of a task, while production events will happen at the end of a task. The consumption profile over all cycles is used as the demand data input of the raw material and finished product inventory policies, and this is where the coordination between inventory and scheduling happens. The inventory policy used for this integrated framework is the (s, Q) policy as implemented for and tested in a commercial project [6]. The next section presents the results.

5 Results and Discussion

The first result of interest to the factory operators is the visualisation of coordinated inventories. Figure 3 shows the inventory level of all four raw materials over all cycles of production. The horizontal line represents the reorder point s, while the dashed vertical lines mark the end of each demand cycle. Whenever the inventory level falls below the reorder point of 150, orders of fixed quantities 178, 154, 203 and 149 are placed. In this figure, the replenishment lead time L is 1 period, so the replenishment activities happen almost immediately after the inventory level drops below the horizontal line. The graph could warn the operators that there is a risk of running out of raw material 2 at the end of the fourth production cycle, or that no reorders of raw material 4 are necessary during the fifth cycle, for example. Another result of interest is the visualisation of coordination between inventories of raw materials and finished products. Figures 4a and 4b show the consumption of materials respect to the finished product they are allocated to. Note that consumption is cumulative over every demand cycle. Figure 4c shows when and how many finished products are manufactured across the production horizon. These figures can help operators understand the allocation of materials for every finished product, especially when the demand of finished products varies greatly between cycle.

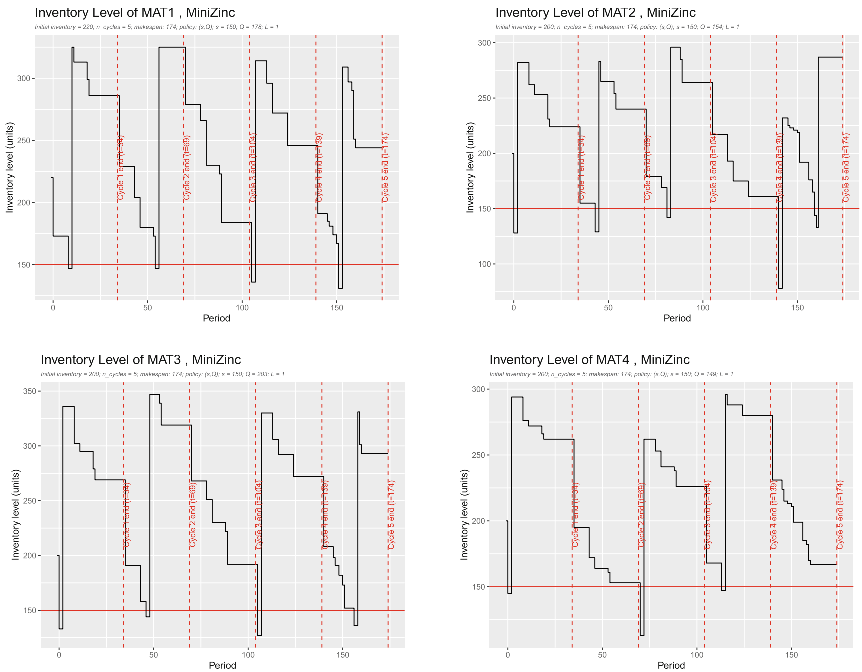
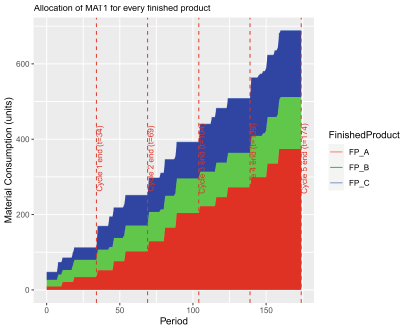
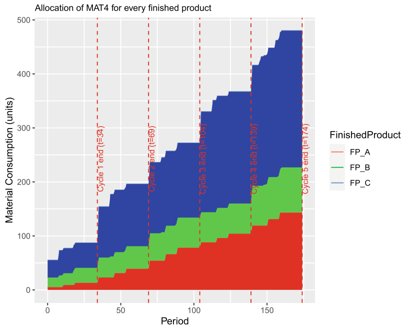


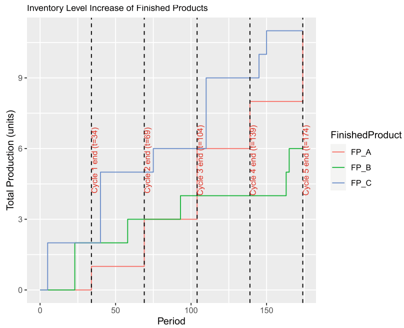
Fig. 3. Inventory plots showing coordinated consumption of raw materials MAT1 to MAT4. The reorder point is 150 for all raw materials and the order quantities are 178, 154, 203 and 149 for raw materials 1 to 4. The reorder time is 1 in all cases.



(a) Allocation of raw material MAT1 for every finished product.



(b) Allocation of raw material MAT4 for every finished product.



(c) Corresponding production of every finished product over the same time frame.

Fig. 4. Visualisation of coordination between inventories of raw materials (a, b) and production of finished products (c).

6 Conclusions and Further Work

On the one hand, Industry 4.0 promises the transformation of manufacturing through new digital technologies, especially to increase sustainability through the rationalisation of resources in real time. On the other hand, many proven methodologies like Lean Manufacturing and Six Sigma could benefit from increased digitalisation and add flexibility to SME operations. In this paper, we claim that the enhancement of existing LM and related methodologies with digital techniques is necessary to make Industry 4.0's promise a reality. To demonstrate it, we presented a proof-of-concept system that combines CP and inventory management to address a combined reactive scheduling and inventory management problem. The proposed framework is designed to be adaptable and easily extended into a more advanced system. The schedule can be altered to represent changes in the production plans, the demand can be fine-tuned according to DM analyses, and the inventory management policies can also be modified according to the needs of the company. This gives greater oversight and encourages better use of resources, improving sustainability.

Our results show that inventories of raw materials and finished products can be coordinated through automated, reactive scheduling, as the production plan can be modified in case of disruption and the effects can be immediately detected in the inventory levels. Of especial interest to operators is the visualisation in real time of likely stock-outs and of consumption rates of materials in synchrony with the production cycle. Despite using simplified models and policies, this proof-of-concept framework provides the groundwork for a real-time, Industry 4.0 platform for manufacturing environments. Future work will emphasise the analysis of uncertainty when optimal scheduling is the link between raw material and finished product inventories. In summary, the proposed framework adapts to the changing conditions in the production floor, can handle inventories of multiple items simultaneously, is modular, focuses on inventory rather than using inventories as buffers to distribution, and rationalises the use of resources to ensure sustainability.

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References

1. Applegate, D., Cook, W.: A computational study of the job-shop scheduling problem. ORSA J. Comput. **3**(2), 149–156 (1991)
2. Barták, R.: Visopt ShopFloor: on the edge of planning and scheduling. In: Van Hentenryck, P. (ed.) International Conference on Principles and Practice of Constraint Programming. LNCS, vol. 2470, pp. 587–602. Springer, Heidelberg (2002). https://doi.org/10.1007/3-540-46135-3_39
3. Buer, B., Strandhagen, J., Chan, F.: The link between industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda. Int. J. Prod. Res. **56**(8), 2924–2940 (2018)
4. Cheng, B., Leung, J., Li, K.: Integrated scheduling on a batch machine to minimize production, inventory and distribution costs. Eur. J. Oper. Res. **258**(1), 104–112 (2017)
5. Fumero, F., Versellis, C.: Synchronized development of production, inventory, and distribution schedules. Transp. Sci. **33**(3), 330–340 (1999)
6. García-Flores, R., Tartaglia, E., Huston, C.: Inventory policies for a manufacturing SME. Technical report EP20545, CSIRO Data61 (2020)
7. Gomes, M., Barbosa-Póvoa, A., Novais, A.: Reactive scheduling in a make-to-order flexible job shop with re-entrant process and assembly: a mathematical programming approach. Int. J. Prod. Res. **51**(17), 5120–5141 (2013)
8. Gunn, E., McDonald, C., Friars, A., Caissie, G.: Scotsburn Dairy Group uses a hierarchical production scheduling and inventory management system to control its ice cream production. Interfaces **44**(3), 253–267 (2014)
9. Lee, I., Yoon, S.: Coordinated scheduling of production and delivery stages with stage-dependent inventory holding costs. Omega **38**(6), 509–521 (2010)
10. Luo, H., Huang, G., Qu, T.: Divergent production scheduling with multi-process routes and common inventory. Int. J. Prod. Res. **51**(3), 828–846 (2012)
11. Man, K., Tang, K., Kwong, S., Ip, W.: Genetic algorithm to production planning and scheduling problems for manufacturing systems. Prod. Plann. Control **11**(5), 443–458 (2000)

12. Nethercote, N., Stuckey, P.J., Becket, R., Brand, S., Duck, G.J., Tack, G.: MiniZinc: towards a standard CP modelling language. In: Bessière, C. (ed.) Principles and Practice of Constraint Programming. LNCS, vol. 4741, pp. 529–543. Springer, Heidelberg (2007). https://doi.org/10.1007/978-3-540-74970-7_38
13. Relvas, S., Matos, H., Barbosa-Póvoa, A., Fialho, J.: Reactive scheduling framework for a multiproduct pipeline with inventory management. Ind. Eng. Chem. Res. **46**(17), 5659–5672 (2007)
14. Rosin, F., Forget, P., Lamouri, S., Pellerin, R.: Impacts of Industry 4.0 technologies on Lean principles. Int. J. Prod. Res. **58**(6), 1644–1661 (2020)
15. Rüttimann, B., Stöckli, M.: Lean and Industry 4.0 – twins, partners, or contenders? A due clarification regarding the supposed clash of two production systems. J. Serv. Sci. Manag. **9**, 485–500 (2016)
16. Schutt, A., Feydy, T., Stuckey, P.J., Wallace, M.G.: Explaining the cumulative propagator. Constraints **16**(3), 250–282 (2011). https://doi.org/10.1007/s10601-010-9103-2
17. Silver, E., Pyke, D., Peterson, R.: Inventory Management and Production Planning and Scheduling, 3rd edn. Wiley, Hoboken (1998)
18. Takeda Berger, S., Zanella, R., Frazzon, E.: Towards a data-driven predictive-reactive production scheduling approach based on inventory availability. In: Proceedings of the 9th IFAC/IFIP/IFORS/IISE/INFORMS Conference on Manufacturing Modelling, Management and Control (IFAC MIM), Berlin, vol. 52, pp. 1343–1348. Elsevier, August 2019
19. Yin, Y., Yang, Y., Wang, D., Cheng, T., Wu, C.: Integrated production, inventory, and batch delivery scheduling with due date assignment and two competing agents. Naval Res. Logist. **65**(5), 393–409 (2018)

Additive Manufacturing in the Automotive Industry and the Potential for Driving the Green and Electric Transition

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Abstract. The dawn of mainstream electric vehicles is here, with almost all major automotive manufacturers now offering fully electric alternatives to traditional internal combustion-based cars. This is in alignment with major trends in sustainability in today's world where a reduction in the usage of fossil fuels and other fossil fuel-dependent technologies is being realized. Additive Manufacturing technologies that have in the past been driven by the automotive industry, now present an opportunity for the automotive sector, where greater gains and benefits can be made by its adoption. Additively manufactured parts enable complex optimized design and also promote material efficiency. Moreover, system wide benefits in terms of streamlined supply chains and logistics operations are also possible and promised. This manuscript presents these benefits, the reason for the growing interests and an outlook for the future of integrated, metal- and polymer-based, additive manufacturing within traditional automotive manufacturing process chains.

Keywords: Additive manufacturing · Automotive manufacturing · Electric Mobility · Sustainability

1 Introduction

1.1 Additive Manufacturing – Driving and Driven by the Automotive Industry

Additive Manufacturing (AM) also known as 3D Printing technologies comprise of a plethora of manufacturing processes that enable the layer by layer manufacturing various parts and components [1]. It has enabled complex designs and enhanced functionalities. The advent of additive manufacturing is also attributed to early adoption by the automotive industry [2]. The automotive industry was one of the first to employ AM processes

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such as laser powder bed fusion (L-PBF), fused filament fabrication (FFF), and more recently inkjet printing as well as stereolithography for the building of prototypes and test pieces. This led to early usage of AM processes to be termed rapid prototyping.

However, over the years AM process have steadily developed both in terms of part precision and quality, as well as process repeatability and reliability. Both of which have so far not deemed to be sufficiently high enough for realization within the automotive industry, where standardized, repeatable and automated processes are an absolute requirement. This juncture for AM processes comes at a time of major transition also for the automotive industry. Especially, automotive industry currently sees major shifts in trends, largely driven by a growing demand for electric mobility as sustainable alternatives for internal combustion engine-based locomotion, which has been the norm since the invention of the automobile [3]. This is further supported by shifts in ideas regarding urban and social mobility through concepted such as ride-sharing, automated driving etc. This paper presents a case for increased adoption and applicability of AM processes within automotive production as AM transitions from prototyping to production and as the automotive industry transitions towards electric and smart mobility [4].

1.2 Metal AM and Increased Efficiency

Metal based AM technologies such as Laser Powder bed fusion (L-PBF), Electron Beam Melting (EBM) etc. have historically been the most popular methods for industrial application and research [5]. Primarily due to the high-performance alloys that were available for printing. Alloys that otherwise could not be machined economically without having to use specialized fabrication processes. Lightweight and advanced alloys of metals such as Titanium and Nickel offer excellent mechanical properties such as high fatigue strength [6].

Major strides have been made in development of final quality of metal additive manufactured parts, achieved through increased research efforts focused on improving the precision of AM processes[7, 8]. These have in recent years encouraged the creation of further business models for AM processes and industrial adoption within the automotive industry [9]. Especially within metal AM processes, the achievable size of components over the recent years has increased drastically, with which larger batches and capabilities for faster production made possible. Trends in automotive production such as electric mobility have further made metal AM an increasingly interesting and viable option [10].

Metal AM process such as LPBF have made possible printing components generated by generative design and topology optimization, meaning the printing of parts where the structure of the internal volume can be controlled and designed as wished [11]. The benefit being that through topology optimization, computer algorithms can design a part that retains or even improves its performance, while only requiring lower material usage [12]. Furthermore, part designs can be adapted to promote cooling, which further improves efficiency during performance.

Efficiency in the key word for the future of electric vehicles, since improved efficiency translates directly into improved range and battery performance, which is the most important factor for all electric-based automotive subsegments, including compact cars, luxury as well as high performance vehicles. Other issues mentioned apart from heat management is the reduction of design space and need for overall reduction in weight, while still maintaining strength need to be addressed. Research has suggested the adoption of additively manufacturing parts in load bearing sections that inherently promote cooling actively and passively, as well as front end components that promote and channel airflow towards high temperature battery and brake systems [13].

Improved efficiency and overall mass reduction in order to improve performance-to-weight rations will be the motivator for metal AM for further integration with automotive components. It is foreseen that in the future, cars, trucks and other automobile will be enriched by metal AM components that will be integrated within hybrid process chains, optimizing the strength-to-weight ratio through advanced component design and reduced sub-assemblies [13].

1.3 Polymer Based AM and New Opportunities

The advent of layer wise manufacturing technologies, have introduced and popularize new terms such as "functional printing" and more recently "industrial printing". The term "functional printing" refers to the enhancing of existing AM technologies to the point of being able to create fully functional printed devices as ready-made products in a single manufacturing process. Technologically speaking, the concept of "industrial printing" can be understood in the context of AM processes as being an integrated asset of the manufacturing process chain and is aimed to contribute to the production processes by adding functionality to the fabricated part or enhancing existing ones.

Chief among other polymer-based AM technologies, inkjet printing has shown a high capability to fabricate functional components made of multiple materials with 3D intricate features. With ability of on-demand digital jetting, inkjet has seen successful implementations to produce 3D printed components of high resolution and integrated functionality [15, 16] (Fig. 1).

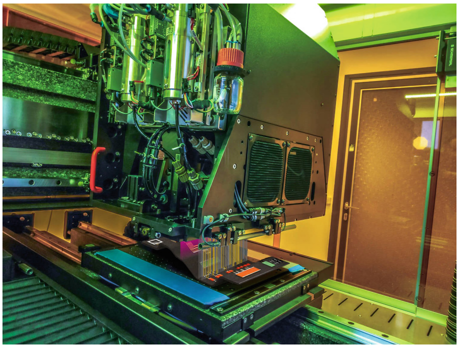

Fig. 1. Illustration of an on-demand multi-material inkjet printing platform with fully functional 3D printed product

Over the last decades, inkjet printing has seen noticeable adoption by industrial community for successful applications ranging from printed electronics, smart sensors, bioinspired components, micro- and 4D active devices and drug delivery [17]. The successful implementation of inkjet technology in industrial applications can be understood due to the limitless design capability that can be printed, along with the high throughput and flexibility at the same time, even a one-off lot size with customized features is possible with the ability for abrupt switching from one design to another [17].

Inkjet technology was successfully applied to print conductive patterns that were then vacuum foamed around a 3D part for capacitive touch sensory applications [18]. The reported research study showcased the ability of inkjet to print and produce flexible touch sensitive sensors. With the use of a vacuum foaming these sensors can be mapped onto different geometries. This could be used to integrate sensing functionality to complex geometries inside and/or outside a vehicle, for example door handles or inside the interior of the vehicle. These implementations can also be applied for automotive infotainment applications. However, with the mature touch sensing functionality that can be integrated/ink jetted to 3D devices such as Human Machine interfaces (HMI), new automotive specific functions/features can be further explored and enhanced.

In another application, flexible sensors, were produced by inkjet printing. In this case the printed sensor has the ability to detect carbon monoxide, which can be used for safety applications. These sensors could be used inside the interior of the car, to monitor the CO levels present inside of the vehicle, and its level in the exhaust gas as well [19]. Similar sensors capable of detecting other gases can also be printed by inkjet process for usage within automobiles.

As automotive industry is also moving towards sustainable fuel sources, hydrogen gas is one of the promising fuels. In this context, inkjet printing is used to create several components of a hydrogen fuel cell. Through the use of inkjet, the manufacturing costs as well as the effectiveness of those fuel cells can be improved. This could be a promising way to effectively produce hydrogen fuel cells for future automobiles [20].

In a recent study the ability of inkjet printing to produce polymer organic light-emitting diodes (PLED) was examined. These PLED seem to also be flexible and through the use of inkjet printing, the accuracy seems to be of good level. This could be used for display inside cars, that are not limited to a flat screen. If this could be combined with the previously mentioned flexible touch sensors, touchscreen display not limited by geometry could be possible [21].

One more application of inkjet technology for automotive industry was the usage of inkjet printing for the production of respiratory sensors, which appears to be low cost and effective. The study mentioned the use in smaller clinic, as the cost for conventional sensors is comparatively high. Nonetheless this wearable sensor could also be integrated inside the driver's seatbelt. In this way the driver's respiratory system could be measured during driving in real time. These values could then be used for safety features [22].

1.4 Potential for AM as an Enabling Technology for the Electric Transition

Within the automotive industry, the shift from conventional towards electric cars as well as the ever-growing speed of the production cycles are changing the requirements for economic success within the market. This development is complemented by the growing political and societal demand for sustainable production.

In electric cars, apart from the obvious improvement of the batteries, range extension can also be achieved by reducing weight and by adopting more efficient management or reduction of electric consumers within the car. While the second factor can be tackled by classical research and development within the company and the suppliers of the electrical components, additive manufacturing can play an important role to reduce weight and can also optimize sustainability of production and supply along the way.

While traditional metal forming is limited to certain structures by the available production techniques and often has time-consuming production cycles for parts and equipment, AM provides us with the opportunity to implement bio-inspired structures, e.g. honeycomb structures, that offer several benefits along the supply chain. The use of structures like the honeycomb facilitate the creation of products that are comparable to or even more stable when compared to a fully dense component, while requiring less raw material in its production process. As a consequence, less raw material needs to be mined/exhausted (metal/plastic), processed and supplied. Incidentally, the weight reduction of production equipment that needs to be processed or moved by machinery or robots during the process, e.g. pressing and gripping, reduces the energy requirement that is needed [23]. Thus, reducing the CO2 footprint of the product and accelerated accomplishment of CO2 neutrality for the equipment and the company.

Additionally, the technical opportunities of AM can be used to further optimize the parts, e.g. by directly including cooling channels that could not have been otherwise obtained by traditional metal forming processes, to create a better and stronger product and a further optimized process. Other optimizations could include the functional printing of body shop equipment, like grippers, fixtures, holders, with built-in sensors [24].

While these isolated changes seem to be rather insignificant at first glance, they come with large consequences if applied on a broad basis. Reducing the complexity of the global supply chain and, essentially, of the company's global carbon footprint (/energy savings) are a direct consequence of a large-scale AM production of complex structures on site. Assembling a complex component at a specialized distributor's production site requires a large supply chain composed of different subparts and raw materials to be shipped between several suppliers and sub-suppliers, sometimes over several countries. These suppliers and sub-suppliers also require large amounts of material to build the forms the production equipment for manufacturing the parts and consume substantial energy to run their production processes, leading to a large material and energy build-up along the supply chain, which can be largely avoided by on-site AM manufacturing [25]. Moreover, raw material for the printers can be packed more densely than finished products, semi-finished products or components, so less shipping units are required to transport raw materials for a specific number of units than for shipping the same number of finished products. This is true for both polymer and metal printing.

While these advantages of AM are rather obvious, more benefits become thinkable by further optimizing AM-driven production and unlocking deeper benefits. Traditionally, companies can either choose to keep the factories small by reducing production depth, leading to complex logistics to avoid production stops, or re-quire storage and warehousing and/or space for production, which comes at the cost of significant space requirements and leads to large and expensive factories. In contrast, AM equipment has the potential to be stackable, making space-saving vertical multi-level production structures with printer farms a real possibility, for production equipment, components as well as spare parts.

2 Conclusions and Outlook

This paper has presented briefly the current outlook for the usage of additive manufacturing technologies within the context of the automotive industry, that is in the midst of a disruptive transformation in terms of focus towards e-mobility and sustainability as well as business models. AM technologies have shown promise especially in the following aspects:

1. Metal AM technologies have the potential to improve efficiency of automobiles through increasing the capacity for design optimised parts. Which will contribute towards high fuel efficiencies and range for electric cars.
2. Inkjet technology has the potential to play a significant role as an enabling technology towards green, smart and electric automotive industry for applications such as smart human machine interfaces, sensors, in hydrogen fuel cells, polymer organic light-emitting diodes and respiratory sensors for the driver etc.
3. AM processes in general provide the option for product innovation through opportunities for reducing production depth, supply chain optimisation and the resulting cost reduction as well.
4. AM processes also contribute toward logistics and production process innovations through introducing concepts such as vertical multi-level production structures and a reduced need for worldwide transportation. Which in turn has the associated benefits for improved sustainability.

The outlook for AM and its involvement with the automotive industry, remain promising and it is one that is expected by all metrics to continue to grow and develop. Combination with other digitalisation topics such as AI, machine learning etc. will only complement the growth outlook for both AM and automotive manufacturing. Therefore, research efforts focussing on these areas needs to be further picked up and nurtured.

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References

1. Yadroitsev, I., Yadroitsava, I.: A step-by-step guide to the L-PBF process. In: Yadroitsev, I., Yadroitsava, I., du Plessis, A., MacDonald, E. (eds.) Fundamentals of Laser Powder Bed Fusion of Metals, pp. 39-77. Elsevier (2021)
2. Lopez, E., Brueckner, F., Gruber, S.: 21 - Industrial applications. In: Yadroitsev, I., Yadroitsava, I., du Plessis, A., MacDonald, E. (eds.) Fundamentals of Laser Powder Bed Fusion of Metals, pp. 583-595. Elsevier (2021)
3. Kester, J., Sovacool, B.K., Noel, L., de Rubens, G.Z.: Between hope, hype, and hell: Electric mobility and the interplay of fear and desire in sustainability transitions. Environ. Innov. Soc. Transit. **35**, 88–102 (2020)

4. Kurosz, J., Milecki, A.: The idea of "Industry 4.0" in car production factories. In: Burduk, A., Chlebus, E., Nowakowski, T., Tubis, A. (eds.) ISPEM 2018. AISC, vol. 835, pp. 597–607. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-97490-3_57
5. Sun, S., Brandt, M., Easton, M.: Powder bed fusion processes. In: Brandt, M. (ed.) Laser Additive Manufacturing, pp. 55–77. Woodhead Publishing, Sawston (2017)
6. Ngo, T.D., Kashani, A., Imbalzano, G., Nguyen, K.T.Q., Hui, D.: Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composit. Part B-Eng. **143**, 172–196 (2018)
7. Charles, A., Elkaseer, A., Paggi, U., Thijs, L., Hagenmeyer, V., Scholz, S.: Down-facing surfaces in laser powder bed fusion of Ti6Al4V: effect of dross formation on dimensional accuracy and surface texture, Addit. Manuf. **46**, 102148 (2021)
8. Charles, A., Elkaseer, A., Thijs, L., Scholz, S.G.: Dimensional errors due to overhanging features in laser powder bed fusion parts made of Ti-6Al-4V. Appl. Sci. Basel **10**(7), 2416 (2020)
9. Wohlers, T.T., Associates, W., Campbell, R.I., Caffrey, T., Wohlers Report 2016: 3D Printing and Additive Manufacturing State of the Industry: Annual Worldwide Progress Report, Wohlers Associates (2016)
10. Llopis-Albert, C., Rubio, F., Valero, F.: Impact of digital transformation on the automotive industry. Technol. Forecast. Soc. Change **162**, 120343 (2021)
11. Jankovics, D., Barari, A.: Customization of automotive structural components using additive manufacturing and topology optimization. IFAC-PapersOnLine **52**(10), 212–217 (2019)
12. Mantovani, S., Presti, I.L., Cavazzoni, L., Baldini, A.: Influence of manufacturing constraints on the topology optimization of an automotive dashboard. Procedia Manuf. **11**, 1700–1708 (2017)
13. Lunetto, V., et al.: Additive manufacturing for an urban vehicle prototype: re-design and sustainability implications. Proc. CIRP **99**, 364–369 (2021)
14. Paritala, P.K., Manchikatla, S., Yarlagadda, P.K.D.V.: Digital manufacturing- applications past Current, and Future Trends. Proc. Eng. **174**, 982–991 (2017)
15. Elkaseer, A.M., Scholz, A., Scholz, S.: Features detection-based image processing of transparent 3D inkjet printed parts. In: A. K., K.S., B. R. (eds.) Proceedings of the Future Technologies Conference (FTC) 2021. Advances in Intelligent Systems and Computing, Springer, Cham (2021). Paper accepted
16. Elkaseer, A., Schneider, S., Scholz, S.: Geometrical-based simulation of drop-on-demand 3D inkjet printing. In: H.R.J. Scholz S.G., Setchi R (ed.) Sustainable Design and Manufacturing 2021. Smart Innovation, Systems and Technologies. Springer, Singapore (2021). Paper accepted
17. Zapka, W.: Handbook of Industrial Inkjet Printing: A Full System Approach. Wiley , Hoboken (2017)
18. Basak, I., et al.: Inkjet printing of PEDOT:PSS based conductive patterns for 3D forming applications. Polymers **12**(12), 2915 (2020)
19. Zuo, J., et al.: Additive manufacturing of a flexible carbon monoxide sensor based on a SnO2-graphene nanoink. Chemosensors **8**(2), 36 (2020)
20. Tamaki, Y., Sugiura, K.: Influence of the catalyst layer structure formed by inkjet coating printer on PEFC performance. Polymers **13**(6), 899 (2021)
21. Amruth, C., Luszczynska, B., Rekab, W., Szymanski, M.Z., Ulanski, J.: Inkjet printing of an electron injection layer: new role of cesium carbonate interlayer in polymer OLEDs. Polymers **13**(1), 80 (2021)
22. Al-Halhouli, A.A., Al-Ghussain, L., El Bouri, S., Liu, H., Zheng, D.: Fabrication and evaluation of a novel non-invasive stretchable and wearable respiratory rate sensor based on silver nanoparticles using inkjet printing technology. Polymers **11**(9), 1518 (2019)

23. Böckin, D., Tillman, A.-M.: Environmental assessment of additive manufacturing in the automotive industry. J. Cleaner Prod. **226**, 977–987 (2019)
24. Schuh, G., Bergweiler, G., Lichtenthäler, K., Fiedler, F., de la Puente Rebollo, S.: Topology optimisation and metal based additive manufacturing of welding jig elements. Proc. CIRP **93**, 62–67 (2020)
25. Delic, M., Eyers, D.R.: The effect of additive manufacturing adoption on supply chain flexibility and performance: an empirical analysis from the automotive industry. Int. J. Product. Econ. **228**, 107689 (2020)

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