Smart Innovation, Systems and Technologies 338

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

# Sustainable Design and Manufacturing

## Proceedings of the 9th International Conference on Sustainable Design and Manufacturing (SDM 2022)

KES International

Springer

# Smart Innovation, Systems and Technologies

Volume 338

The Smart Innovation, Systems and Technologies book series encompasses the topics of knowledge, intelligence, innovation and sustainability. The aim of the series is to make available a platform for the publication of books on all aspects of single and multi-disciplinary research on these themes in order to make the latest results available in a readily-accessible form. Volumes on interdisciplinary research combining two or more of these areas is particularly sought.

The series covers systems and paradigms that employ knowledge and intelligence in a broad sense. Its scope is systems having embedded knowledge and intelligence, which may be applied to the solution of world problems in industry, the environment and the community. It also focusses on the knowledge-transfer methodologies and innovation strategies employed to make this happen effectively. The combination of intelligent systems tools and a broad range of applications introduces a need for a synergy of disciplines from science, technology, business and the humanities. The series will include conference proceedings, edited collections, monographs, handbooks, reference books, and other relevant types of book in areas of science and technology where smart systems and technologies can offer innovative solutions.

High quality content is an essential feature for all book proposals accepted for the series. It is expected that editors of all accepted volumes will ensure that contributions are subjected to an appropriate level of reviewing process and adhere to KES quality principles.

Indexed by SCOPUS, EI Compendex, INSPEC, WTI Frankfurt eG, zbMATH, Japanese Science and Technology Agency (JST), SCImago, DBLP.

All books published in the series are submitted for consideration in Web of Science.

More information about this series at https://link.springer.com/bookseries/8767

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

# Sustainable Design and Manufacturing

## Proceedings of the 9th International Conference on Sustainable Design and Manufacturing (SDM 2022)

Springer

*Editors*
Steffen G. Scholz
Karlsruhe Institute of Technology
Karlsruhe, Germany

Robert J. Howlett
KES International Research
Shoreham-by-sea, UK

Rossi Setchi
School of Engineering
Cardiff University
Cardiff, UK

ISSN 2190-3018 ISSN 2190-3026 (electronic)
Smart Innovation, Systems and Technologies
ISBN 978-981-19-9204-9 ISBN 978-981-19-9205-6 (eBook)
https://doi.org/10.1007/978-981-19-9205-6



This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

# Preface

Over the last two decades, dramatic changes in market demands have played a significant role in the revolution of the manufacturing paradigm from one based on mass production of traditional parts towards customized and highly functionalized products. This transformation of the manufacturing models has been associated with development in the manufacturing processes, systems and strategies. In particular, resource-efficient production is one of the Industry 4.0 key aspects for keeping both unnecessary costs and environmental impact of a modern processing route to minimum. In this regard, the SDM-22 offers unique opportunities for the keynote talks, oral presentations, general tracks, invited sessions and discussion about the thematic topic “sustainable design and manufacturing”, leading to knowledge exchange and the generation of new ideas. SDM-22 is a special event, held after the COVID-19 crisis, in which we are excited to meet in person. I and my KES International would like to welcome you all to this volume, which forms the proceedings of the ninth KES International Conference on Sustainable Design and Manufacturing (SDM-22), organized by KES International between 14 and 16 September 2022, in Split Croatia.

SDM conferences have always attracted excellent contributions, for which we are grateful, we are also pleased to see so many new contributors to SDM-22. 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.

This physical conference proved an excellent stage for the presentation of state-of-the-art research and for conducting deep scientific discussions about 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 eight 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); and the University of York, York, UK, and held in Budapest, Hungary (2019), in addition to the virtual conferences during the COVID-19 crisis (2020 & 2021).

Once again, the conference was comprised of 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.

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-22 was of the high standard required by Springer Nature proceedings.

Steffen G. Scholz
SDM-22 General Programme Chairs

# Organization

## International Programme Committee

| | |
|---|---|
| Emmanuel Adamides | University of Patras, Greece |
| Y. W. R. Amarasinghe | University of Moratuwa, Sri Lanka |
| Johanna Esguerra Arce | Escuela Colombiana de Ingeniería Julio Garavito, Colombia |
| Peter Ball | University of York, UK |
| Alain Bernard | Ecole Centrale de Nantes, France |
| Nadia Bhuiyan | Concordia University, Canada |
| Samuel Bigot | Cardiff University, UK |
| Marco Bortolini | Bologna University, Italy |
| Leszek Borzemski | Wroclaw University of Technology, Poland |
| Kai Cheng | Brunel University, UK |
| Wai Ming Cheung | Northumbria University, UK |
| Ahmed Elkaseer | Karlsruhe Institute of Technology, Germany |
| Daniel Eyers | Cardiff University, UK |
| Antonio Gagliano | University of Catania, Italy |
| Francesco Gabriele Galizia | University of Bologna, Italy |
| Quanquan Han | Shandong University, China |
| Maria Holgado | University of Sussex, UK |
| Luisa Huaccho Huatuco | University of York, UK |
| Haihong Huang | Hefei University of Technology, China |
| Winifred Ijomah | University of Strathclyde, UK |
| Assoc. Giuseppe Ingarao | University of Palermo, Italy |
| Alessio Ishizaka | NEOMA Business School, France |
| I. S. Jawahir | University of Kentucky, USA |
| Stefan Junk | Offenburg University of Applied Sciences, Germany |
| Jayakrishna Kandasamy | Vellore Institute of Technology, India |
| Olivier Kerbrat | ENS Rennes, France |

| | |
|---|---|
| Ong Soh Khim | National University of Singapore |
| Gul Kremer | Iowa State University, USA |
| Minna Lammi | Anglia Ruskin University, UK |
| Chi Hieu Le | University of Greenwich, UK |
| Fiona Lettice | University of East Anglia, UK |
| Huaizhong Li | Griffith University, Australia |
| Soon Chong Johnson Lim | Universiti Tun Hussein Onn Malaysia (UTHM) |
| Andrew Longstaff | University of Huddersfield, UK |
| Jillian MacBryde | University of Strathclyde, UK |
| Sinead Mitchell | National University of Ireland |
| James Moultrie | University of Cambridge, UK |
| Mohamed Naim | Cardiff University, UK |
| Mohamed Osmani | Loughborough University, UK |
| Michael Packianather | Cardiff University, UK |
| Emanuele Pagone | Cranfield University, UK |
| Paolo C. Priarone | Politecnico di Torino, Italy |
| Laura Purvis | Cardiff University, UK |
| Caterina Rizzi | University of Bergamo, Italy |
| Federico Rotini | University of Florence, Italy |
| Mahmoud Salem | Karlsruhe Institute of Technology, Germany |
| Ernesto Santibanez-Gonzalez | University of Talca, Chile |
| Steffen G. Scholz | Karlsruhe Institute of Technology, Germany |
| Tiziana Segreto | University of Naples Federico II, Italy |
| Rossi Setchi | Cardiff University, UK |
| Johann Sienz | Swansea University, UK |
| Cristian Spreafico | University of Bergamo, Italy |
| Qian Tang | Chongqing University, China |
| Yuchun Xu | Aston University, UK |
| Hong-Chao Zhang | Texas Tech University, USA |
| Hua Zhang | Wuhan University of Science and Technology, China |
| Zhinan Zhang | Shanghai Jiao Tong University, China |

# Contents

# About the Editors

**Steffen G. Scholz** is the head of the group “Process optimization, Information management and Applications”, part of the Institute for Automation and Applied Informatics (IAI), Karlsruhe Institute of Technology. He is also the principal investigator in the Helmholtz funded long-term programmes “Digital System integration” and “Printed Materials and Systems”. He has more than 15 years of experience in the field of system integration and automation, sustainable flexible production, polymer micro- and nano-replication, process optimization and control, with a recent emphasis on additive manufacturing and Industry 4.0 applications. In addition to pursuing and leading research, he has been very active with knowledge transfer to industry. He has been involved in over 30 national and international projects, and he won in excess of 20M EUR research grants, in which he has acted as the coordinator and/or the principal investigator. Dr. Scholz academic output includes more than 150 technical papers and 5 books. He is an honorary professor at Swansea University and a visiting professor at Vellore Institute of Technology (VIT) in India.

**Robert J. Howlett** is the academic chair of KES International a non-profit organization which facilitates knowledge transfer and the dissemination of research results in areas including intelligent systems, sustainability, and knowledge transfer. He is a visiting professor at “Aurel Vlaicu” University of Arad, Romania and has also been a visiting professor at Bournemouth University, UK. His technical expertise is in the use of artificial intelligence and machine learning for the solution of industrial problems. His current interests centre on the application of intelligent systems to sustainability, particularly renewable energy, smart/microgrids and applications in housing and glasshouse horticulture. He previously developed a national profile in knowledge and technology transfer and the commercialization of research. He works with a number of universities and international research groups on the supervision teams of PhD students and the provision of technical support for projects.

**Rossi Setchi** is a professor in High-Value Manufacturing and the director of the Research Centre I AI, Robotics and Human-Machine at Cardiff University. She has a distinguished track record of research in a range of areas including AI, robotics, systems engineering, manufacturing, industrial sustainability, cyber-physical systems and Industry 4.0 and, in particular, has built an international reputation for excellence in knowledge-based systems, computational semantics and human–machine systems. She has published over 260 peer-reviewed papers. She is a fellow of the Institution of Mechanical Engineers, a fellow of the Institution of Engineering and Technology, a fellow of the British Computer Society and a senior member of IEEE. She serves as the associate editor/member of the Editorial Board of a number of international journals.

# Impact of Additive Manufacturing on Supply Chains

Elisa Lauth[1] and Steffen G. Scholz[1,2,3](✉)

[1] Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshofen, Germany
{elisa.lauth,steffen.scholz}@kit.edu

[2] Karlsruhe Nano Micro Facility (KNMF), Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany

[3] Future Manufacturing Research Institute, College of Engineering, Swansea University, Swansea SA1 8EN, UK

**Abstract.** Technologies are evolving over time and some innovations can result in disruptive changes which lead to transformations in companies and their supply chains. Three-dimensional printing (3DP) has high disruptive potential as it is becoming increasingly relevant as a production technology. Hence, it is of significant importance to investigate the current and future impacts of 3DP on supply chains. The state of the art provides an overview of supply chain management as well as the production aspects of additive manufacturing. Moreover, impact factors of 3DP on supply chains have been identified. To further investigate the current and future impacts of 3DP on supply chains, five interviews with technical experts have been conducted. The analysis of the interviews shows that the companies have sensed changes in their supply chains. However, most of these changes regard prototyping and there have not been drastic changes in the production of end products. Current impacts have been identified in mass customization, resource efficiency, rationalization of inventory and logistics as well as prototyping and product design. Future impact is seen overwhelmingly in all impact areas. Moreover, AM will ultimately increase the sustainability of supply chains. Finally, a recommendation for action can be given for companies to implement the technology in small batch sizes and to consider it as a complementary technology.

**Keywords:** 3D printing · Supply chain management · Industry 4.0

## 1 Introduction

As technology evolves over time, new advancements occur. Some of the technological novelties can result in disruptive change [1]. The ongoing technological developments lead to transformations of factories which have impacts on supply chains [2]. Due to the potential disruptive changes, executives must be aware of technological novelties that could impact their organizations and supply chains [1]. Current disruptive technologies are for instance robotics and automation, big data, internet of things as well as three-dimensional printing (3DP) [3].


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 1–10, 2023.
https://doi.org/10.1007/978-981-19-9205-6_1

3DP which is often used synonymously in industrial context with additive manufacturing (AM) [4] describes a manufacturing technique where objects can be built by the addition of materials [5]. 3DP is experiencing a rapid growth [6] and many companies try to follow this trend and further their business endeavors using this new technology [7].

Due to the Covid-19 pandemic the AM community had the opportunity to help in fulfilling local demand and to test the application of 3DP for industrial use [8]. Although the researchers were able to identify the benefits and the usefulness of 3DP in industrial manufacturing, the impact of 3DP on organizations is still underrepresented in research. Since it is of high importance for companies to be aware of disruptive technologies as well as solutions to cope with them, the present study will answer the following research questions: What are the current and future impacts of 3DP on supply chains?

This paper is structured as follows. Section 2 gives a literature review on supply chain management (SCM) as well as AM. Section 3 covers the methodology applied in this paper which is used to analyze the interviews conducted with five selected companies. Then, Sect. 4 illustrates the findings. Thereafter, in Sect. 5 the impact areas identified in the field research will be discussed and recommendations for action formulated for the coping of disruptive technologies such as 3DP. Finally, Sect. 6 provides a brief conclusion and outlook.

## 2 Literature Review

### 2.1 Supply Chain Management

SCM is of high importance in the current business environment. It is generally considered to be one of the best areas which can yield significant advantages over the competition [9], especially due to the optimization possibilities such as cost reductions. Consequently, organizations strive to implement effective SCM [10].

The Global Supply Chain Forum defines SCM as "the integration of key business processes from end user through original suppliers that provides products, services and information that add value for customers and other stakeholders" [11]. Supply chains generally consist of two or more organizations that are linked by information, material, and financial flows. In supply chains there are producing firms that manufacture either components, parts, or end products as well as logistics service provider and customers [12]. In conclusion, SCM generally has three tasks that can be summarized into sourcing raw materials, converting this material into finished products, and then supplying the products. Thus, supply chains can be characterized by a forward flow of material and a backward flow of information [13].

### 2.2 Production Aspects of Additive Manufacturing

The American Society for Testing and Materials defines AM as "the process of joining materials to make objects from 3D model data, usually layer upon layer" [4]. Hence, AM is a revolutionary technology that allows for the building of physical objects based on digital files [7]. Many scholars consider AM to be a disruptive technology [14]. In the early stages of AM, its application was mostly focused on prototyping whereas now it has many more applications [15]. With an increase of usable materials, the number of possible applications has risen drastically [16]. Nowadays AM has the potential to impact manufacturing and provide benefits for producing companies [17]. Consequently, many organizations are interested in the possible benefits 3DP could have in their production [7].

Regarding the evaluation of AM, the production technology is considered to be a more agile and eco-friendly alternative to conventional manufacturing. Nonetheless, the slower manufacturing process as well as few adoptions of AM still limit its applications [8]. Hence, AM is more suitable for small batch production [18]. Moreover, decentralized productions, and higher flexibility that can help with mitigating delays in supply chains, and other problems regarding supply shortages, are a clear advantage of AM which makes it a good alternative for conventional manufacturing [19]. Nevertheless, most scholars agree that 3DP will not make conventional manufacturing obsolete but rather complement these technologies [17]. This is likely since both manufacturing methods suit different productions styles.

### 2.3 Impact of Additive Manufacturing on Supply Chains

Numerous scholars agree on the fact that 3DP has a high disruptive potential regarding its impacts on the logistics industry and global supply chains [20]. As the use of 3DP in the manufacturing and fabrication of goods increases, the possible impacts on the supply chain are of high importance. Especially since it has the potential to presuppose a change in supply chains [21].

The use of 3DP in the production process can be advantageous for many organizations. Principally since it can ensure a complexity reduction of supply chains. Due to the possibility to print on-demand, the need for excessive inventory becomes obsolete. As a consequence, the traditional complex supply chain model is no longer required. In Fig. 1 a new proposed model for supply chains can be seen. As a result, the supply chains with integrated AM become less complex since only the materials along with the digital files are needed for the 3DP. Whereas the focus of traditional supply chains is on the mass-produced goods which are pushed out into the market with high logistics costs and emissions, the supply chain that integrates AM can provide a low volume production with customized products [22].

Apart from the differences in the supply chain structure, seven key impact areas of 3DP on supply chains can be identified. The first impact area concerns the mass customization enabled by 3DP. AM offers the possibility to individualize products for each customer. Due to late-stage postponement customization, the supply chain is thought to be more agile and flexible which ultimately benefits the reaction to late changes in customer requirements [23]. The second impact area of AM is resource efficiency. One of the numerous advantages of AM is the increased resource efficiency of 3DP [8]. Equally important is that the excess material in 3DP can be recycled and reused which endorses the idea of a circular economy. Another important impact area focuses on the decentralization of manufacturing. Due to the possibility to print on-demand, there is a shift of the manufacturing location to the point-of-consumption. This helps in reacting quicker to changes in demand which in turn ensures the flexibility of supply chains [23].

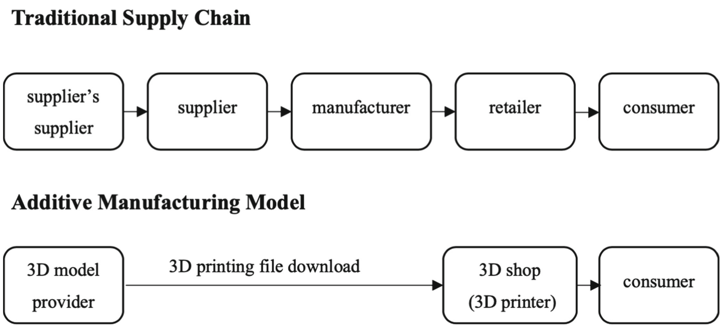



**Fig. 1.** Traditional supply chain and additive manufacturing model [22]

The fourth impact area is the complexity reduction. Supply chains' complexity can be drastically reduced, which is also apparent in Fig. 1. The consolidation of multiple suppliers and the shortening of the manufacturing process can ultimately lead to reduced complexity as well as shorter supply chains [5]. Equally important is the rationalization of inventory and logistics. 3DP enables the production-on-demand at the point of consumption. This leads to reduced demand for global transportation [23]. Moreover, there is no longer a need for excessive inventories [21]. The sixth impact factor is concerned with product design and prototyping. 3DP allows products to take on new forms which would normally not be possible in traditional manufacturing [24]. Moreover, there is a direct digital-to-physical concept. The last impact factor of 3DP consists of legal and security design. This impact area is concerned with legal issues posed by 3DP. Currently, the underlying legal framework is not sufficient [23].

## 3 Methodology

This section focuses on the methodology followed in this study. To evaluate the impact 3DP has on supply chains, interviews were conducted with representative industry experts. For the evaluation, qualitative content analysis was used. The qualitative content analysis method deals with text evaluation in the context of research projects [25]. Concerning the data collection, semi-structured interviews will be used. They allow participants to respond freely and to clarify their opinions [26]. Prior to the conduction of the interviews, an interview guide was created [27].

For the present study, the most important criterion for the participants was their involvement with 3DP in their everyday work. As a result, five experts were acquired. All interviewees are from different companies, ensuring diversity in answers and opinions. All information on the interviewees as well as their companies, are anonymized. Nevertheless, the industry sector is briefly explained. The most important information on the personas is summarized in Table 1. The interviews lasted 30–40 minutes.

**Table 1.** Profile of the interviewees

| Interviewee | Position | Company | Industry sector |
|---|---|---|---|
| Interviewee 1 | Development Engineer | Company A | Automotive Sector |
| Interviewee 2 | Development Engineer | Company B | Plastics Processing Industry |
| Interviewee 3 | Senior Business Development Manager | Company C | Software Solutions for AM |
| Interviewee 4 | Head of 3DP | Company D | Mechanical Engineering / 3DP Service Provider |
| Interviewee 5 | AM Consultant | Company E | 3D Printer Manufacturer |

# 4 Findings

## 4.1 Use and Evaluation of 3D Printing in Selected Companies

All interviewees agree on the fact that AM is mostly used in prototyping or the production of operating tools. Some serial applications can be observed in specific industries such as medicine, aerospace and automotive. Regarding changes in production, it can generally be observed that mainly the development process has changed instead of the actual production. The development of products is quicker, as well as more flexible.

The interviewees see various advantages which can be associated with 3DP. One of the most frequently named aspects was the time reduction. Moreover, it is possible to react quicker since it is easy to print the components needed. However, there are also some limitations according to the interviewees. Firstly, the production process is slower. Moreover, the standardization of the 3DP process is not yet mature.

Regarding the disruptive potential, the interviewees are all in agreement. All of them see that there is a disruptive potential to 3DP and that the technology will disrupt the market to some extent. However, given the disadvantages, the application of AM will be rather complementary than substitutive.

## 4.2 Impact of 3D Printing on Supply Chains in Selected Companies

Since AM is mostly used for prototyping in the interviewees' companies, most of the impact factors identified from the interviewees are associated with the future potential. Nonetheless, the interviewees also described actual impacts they have been able to observe in their supply chains. For instance, Interviewees 1, 3 and 4 claimed that 3DP helped to bridge delivery times. Through 3DP, the required components could be printed directly which resulted in shorter delays.

AM poses the possibility in the given companies to reduce the dependencies from their suppliers since they can print the components they need in case of delays. Despite the fact that critical situations such as supply chain disruptions have already demonstrated that 3DP can decrease dependence on suppliers, Interviewees 2, 3 and 5 see no possibility for this outcome. Nonetheless, all interviewees see opportunities to improve customer experiences. Especially customers can be offered more performance.

Regarding the impact factors, all interviewees see a high impact of AM on mass customization since 3DP offers the possibility of producing a large number of parts with a high degree of individualization. Mass customization is mainly relevant in industries in which the products are directly addressed to customers, such as medicine, eyewear, or sports. The participants elaborate that AM has great potential to enable resource efficiencies. These effects have already been realized in the given companies. Reasons for this include the possibility of recycling and thus reusing printing materials. All interviewees reportedly see the effects on the decentralization of production in the future. Nevertheless, all interviewees see great potential and associated advantages through the increasing decentralization that will take place in the future. So far, almost no participant has noticed any changes in the complexity of supply chains. Some of the participants see a strong potential to reduce the complexity of the supply chains in the future. However, some have the opinion, that supply chains will become more flexible in the future but by no means less complex. In rationalization of inventory and logistics, all interviewees sense a very large potential for optimization and cost savings, but mostly for future applications. Interviewee 4 has already been able to achieve advantages for one of his customers in the field of logistics through the lightweight construction of heavy objects, which can now be transported more easily. All interviewees agree that 3DP is already well represented in prototyping and product design. One aspect is that more individual design can be created more easily. The costs for product development greatly reduced by AM. Some of the interviewees have concerns regarding the legal and security issues posed by 3DP in production. It can be seen as a clear objection that needs to be addressed before mass implementation of AM.

Although the interviewees reported many positive impacts, they see a lot of effort associated with the implementation of AM in supply chains. One of the reasons is the complexity of the technology. Therefore, companies should ask themselves whether they should operate 3DP in-house or whether they would prefer to outsource it. Regarding the supply chain managers, the interviewees see a compelling expansion of skills. They must have know-how to be able to efficiently manage supply chains with AM.

Regarding the future of 3DP all interviewees see a lot of potential for 3DP. They assume that there will be continuous developments of the technology. With a faster and more efficient production process, the technology would be used more often. In general, the interviewees see it as likely that 3DP will be an essential component in manufacturing in the future. Thus, all interviewees recommend investing in 3DP and using it for the production in the future. Particularly high potential can be seen in aerospace, medicine, semiconductors and the chemical industry.

## 5 Discussion

This paper investigates the research question: What are the current and future impacts of 3D printing on supply chains? It can be concluded that there are impacts on supply chains and that there have been changes determined in the selected companies. However, these changes are mostly in the fields of prototyping and bridging critical situations. There have not yet been any drastic changes in the normal supply chains. At least not in the companies selected for this paper. Nonetheless, one can see that there is a great potential for changes in the companies' supply chains, especially because there will be an increasing number of use cases over time. 3DP has proven to be an optimal solution especially in critical times. Nevertheless, 3DP still has a long way to go before it can be widely applied in the production of end products. It is also debated whether the share of AM in the global production market is too small to have vast impacts on supply chains.

Moreover, it can be questioned whether the impact will actually be as extreme as portrayed in the proposed supply chain model. One reason for this is that the technology is predominantly seen as a complementary technology and will therefore only be used in production situations that fit 3DP. These production situations consist primarily of small batch sizes with a high degree of individualization.

Furthermore, it is made clear that 3DP will advance digital production. There are significantly more opportunities for on-demand production in contrast to conventional manufacturing, which encourages companies to avoid overproduction. Moreover, AM offers great potential for decentralizing manufacturing, which is a significant contribution to sustainability. The reason for his is that the need for global transportation is drastically reduced in a distributed manufacturing setup. If AM can ultimately be used in large batch sizes, the impact on supply chains will increase significantly.

It can be summarized that impacts have already been identified in mass customization, resource efficiency, rationalization of inventory and logistics as well as prototyping and product design. Mass customization is mostly relevant in specific customer-oriented industries. Resource efficiency has had impacts in all companies. The rationalization of inventory and logistics was mostly reported by one company. Prototyping and product design is an aspect that all interviewees can agree on and see the 3DP technology as a clear substitute to conventional methods. In addition, there is a significant increase in customer satisfaction and reduction of supplier dependencies due to the possibility to overcome supply chain disruptions and supply chain bottlenecks. Future impact is seen overwhelmingly by most interviewees in all impact areas. Nonetheless, it should be taken into consideration that there are companies that operate entirely with 3DP. It is possible that the results of these companies could differ. Table 2 summarizes the results of the present paper.

**Table 2.** Current and future impacts of 3D printing on supply chains

| Impact factor | Current impact | Future impact |
|---|---|---|
| Mass Customization | Yes | Yes |
| Resource Efficiency | Yes | Yes |
| Decentralization of Production | No | Yes |
| Complexity of Supply Chains | No | Yes and No |
| Rationalization of Inventory and Logistics | Yes and No | Yes |
| Prototyping and Product Design | Yes | Yes |
| Reduction of Dependencies | Yes and No | Yes and No |
| Customer Experience | Yes | Yes |

As a part of the results of this paper, recommendations for action will be provided. The reason for this, as discussed in the introduction, is that the disruptive potential of 3DP can lead to vast transformations in companies. Therefore, recommendations for action will be derived from the results of this study.

Firstly, it is of high importance to clarify which companies should use 3DP in the future. The results of this paper suggest that the potential for 3DP is especially high in aerospace, medical, logistics, automotive, railway, semiconductors and the chemical industry. Nevertheless, the findings show recommendations for all companies to invest in 3DP, as it can lead to optimization potential in companies and bridge disruptions in supply chains. In general, it is recommended in production with small series and a high degree of individualization.

The second aspect of the recommendation for action is concerned with the implementation of AM. Based on the results of this study, it can be deduced that the introduction of 3DP is associated with a high level of effort. It is therefore worth considering outsourcing the 3DP process to service providers. In conclusion, it is critical for companies to acquire knowledge about the technology and its impact. 3DP should initially and most likely in the future be seen as a complementary technology, supplementing conventional methods where it is beneficial. Companies that integrate AM may be more responsive and independent due to the high flexibility in their supply chains.

## 6 Conclusion

This paper is able to identify impact areas of AM on supply chains as well as current and future changes of supply chains. From this, recommendations for action could be derived regarding the future use of 3DP in different industries. The increasing relevance of 3DP in the corporate world has been highlighted. This underlined the importance of this study to investigate the changes of supply chains and to give recommendations for action for companies using 3DP or striving to implement 3DP in their supply chains.

By conducting semi-structured interviews with five selected companies, the use of 3DP in different industry branches, as well as the impacts on their supply chains were examined. The analysis has shown that 3DP is mostly used in prototyping. Hence the impacts on supply chains are still small but nonetheless all interviewees have experienced impacts on the supply chains in their companies due to higher flexibility and shorter lead times. All interviewees see high potential for the further development of the technology. As the objective of this study was to identify current and future impacts of 3DP on supply chains, current impacts could be identified in customer experience, reduction of dependencies, mass customization, resource efficiency, rationalization of logistics, and prototyping and product design. In the future, the impacts on supply chains are going to increase steadily due to a gradually rising number of applications. Especially contributions to sustainability regarding the reduction of the carbon footprint and decreased material wastage can be seen in future applications of AM in supply chains. It is apparent that 3DP can be recommended to all companies due to the high number of benefits, especially on the supply chains.

To ensure more expressive results, more interviews would have to be conducted. Since this study determined that for the selected companies, 3DP is still in early adoption and mostly applied in prototyping as well as in critical situations in their supply chains, future work should assess this topic in a further manner since it is of ongoing importance. It would be best to enlarge the number of participants and assess more industries and companies by applying quantitative research methods. This can help in giving recommendations for action for specific industries. Moreover, it would be recommended to examine companies that exclusively use 3DP in their production since they have possibly experienced greater impacts and changes in their supply chains.

**Acknowledgements.** This work was carried out with the support of the Karlsruhe Nano Micro Facility (KNMFi, www.knmf.kit.edu), a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu) and under the Helmholtz Research Programme STN (Science and Technology of Nanosystems) at KIT.

## References

1. McKinsey Global Institute: Disruptive technologies: advances that will transform life, business, and the global economy (2013)
2. Szozda, N.: Industry 4.0 and its impact on the functioning of supply chains. Sci. J. Logist. **13**(4), 401–414 (2017)
3. DHL Trend Research: Logistics Trend Radar - Version 2014 (2014)
4. ASTM: Standard terminology for additive manufacturing technologies. In: ASTM International F2792-12a (2012)
5. Lim, C.W.J., Le, K.Q., Lu, Q., Wong, C.H.: An overview of 3-D printing in the manufacturing, aerospace, and automotive industries. IEEE Potentials **35**(4), 18–22 (2016)
6. Birtchnell, T., Urry, J.: 3D, SF and the future. Futures **50**, 25–24 (2013)
7. Chan, H.K., Griffin, J., Lim, J.J., Zeng, F., Chiu, A.S.F.: The impact of 3D printing technology on the supply chain: manufacturing and legal perspectives. Int. J. Prod. Econ. **205**, 156–162 (2018)
8. Müller, T., et al.: Eight weeks later - the unprecedented rise of 3D printing during the COVID-19 pandemic - a case study, lessons learned, and implications on the future of global decentralized manufacturing. Appl. Sci. **10**(12), 1–14 (2020)
9. Ibrahim, S.B., Hamid, A.A.: Supply chain management practices and supply chain performance effectiveness. Int. J. Sci. Res. **3**(8), 187–195 (2014)
10. Werner, H.: Supply Chain Management - Grundlagen, Strategien, Instrumente und Controlling, 7th edn. Springer Fachmedien, Wiesbaden (2020)
11. Lambert, D.M., Cooper, M.C., Pagh, J.D.: Supply chain management: implementation issues and research opportunities. Int. J. Logist. Manag. **9**(2), 1–19 (1998)
12. Stadler, H., Kilger, C.: Supply Chain Management and Advanced Planning - Concepts, Models, Software and Case Studies, 3rd edn. Springer, Heidelberg (2005)
13. Beamon, B.M.: Supply chain design and analysis: models and methods. Int. J. Prod. Econ. **55**(3), 281–294 (1998)
14. Berman, B.: 3-D printing: the new industrial revolution. Bus. Horiz. **55**(2), 155–162 (2012)
15. Schneck, M., et al.: Evaluating the use of additive manufacturing in industry applications. Procedia CIRP **81**, 19–23 (2019)
16. Frazier, W.E.: Metal additive manufacturing: a review. J. Mater. Eng. Perform. **23**(6), 1917–1928 (2014). https://doi.org/10.1007/s11665-014-0958-z
17. Huang, S.H., Liu, P., Mokasdar, A., Hou, L.: Additive manufacturing and its societal impact: a literature review. Int. J. Adv. Manuf. Technol. **67**(5), 1191–1203 (2013)

18. McAlister, C., Wood, J.: The potential of 3D printing to reduce the environmental impacts of production. In: ECEEE Industrial Summer Study Proceedings, vol. 213, pp. 213–221 (2014)
19. Tareq, M.S., Rahman, T., Hossain, M., Dorrington, P.: Additive manufacturing and the COVID-19 challenges: an in-depth study. J. Manuf. Syst. **60**, 1–30 (2021)
20. Mohr, S., Kahn, O.: 3D printing and supply chains of the future. Proc. Hamburg Int. Conf. Logist. **20**, 147–174 (2015)
21. Christopher, M.: Logistics & Supply Chain Management, 4th edn. Pearson Education Limited, Dorchester (2011)
22. Kubáč, L., Kodym, O.: The impact of 3D printing technology on supply chain. MATEC Web Conf. **134**, 1–8 (2017)
23. Mohr, S., Kahn, O.: 3D printing and its disruptive impacts on supply chains of the future. Technol. Innov. Manag. Rev. **5**(11), 20–45 (2015)
24. Oettmeier, K., Hofmann, E.: Additive Fertigung und deren Auswirkungen auf Supply Chains. Springer Fachmedien, Wiesbaden (2015)
25. Mayring, P., Fenzl, T.: Qualitative Inhaltsanalyse. Publisher, Wiesbaden (2019)
26. Longhurst, R.: Semi-structured Interviews and focus groups. Key Methods Geogr. **3**(2), 143–156 (2003)
27. Luo, L., Wildemuth, B.M.: Semistructured Interviews, 2nd edn. Publisher, Santa Barbara (2017)

# Introduction and Evaluation of a Project Management Software Tool in the Context of the Administration of Science and Research Projects

Elisa Lauth[1] and Steffen G. Scholz[1,2,3](✉)

[1] Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshofen, Germany
{elisa.lauth,steffen.scholz}@kit.edu
[2] Karlsruhe Nano Micro Facility (KNMF), Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany
[3] Future Manufacturing Research Institute, College of Engineering, Swansea University, Swansea SA1 8EN, UK

**Abstract.** Projects are increasing in complexity in the current business world. This is also evident in a working group of the Institute for Automation and Applied Informatics in the Karlsruhe Institute of Technology. To facilitate project management and tackle overall problems, a project management software has been introduced in the group. This study shows the impact of this introduction. The state of the art provides an overview on the most relevant information on project management, showing the importance and benefits of project management software tools. The current situation in the group is analyzed by conducting semi-structured interviews. Based on a criteria catalogue, the software Microsoft Project is selected to be introduced with four testing project managers. To evaluate the impact the introduction of the software tool had, the situation after the introduction is analyzed. The pre-introduction analysis shows that the current project management approach of the project managers needs changes. The post-introduction analysis shows the impact areas of Microsoft Project. The tool had positive impacts on the project managers, such as keeping a better overview, transparency, structuring and control over projects. All project managers believe that the tool has the potential to improve their project management sustainably in the long run. In conclusion, a recommendation of action can be given to continue the usage of the tool.

**Keywords:** Project management · Information systems · Software introduction

## 1 Introduction

The Karlsruhe Institute of Technology (KIT) consists of over 9000 employees with the majority working in research [1]. In 148 institutes [2], research is conducted in the main topics of energy transition, mobility of the future and technology for the information society [3]. This paper focuses on the Institute for Automation and Applied Informatics


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 11–20, 2023.
https://doi.org/10.1007/978-981-19-9205-6_2

(IAI). This institute consists of various working groups, pursuing research on several projects from different funding agencies [4]. The working group Process Optimization - Information Management - Applications (PIA) is focusing on four main topics: process optimization in the context of Industry 4.0, 3D-printing, decision support systems and nanomaterials safety assessment [5]. The PIA group team members work on a high number of different projects.

In the current business world, projects are increasing in complexity [6]. This is also felt by the project managers of the PIA group, which leads them to be confronted with higher demands for effective project management. This is especially noticed since most of the projects are third-party funded, which concludes a huge variety of complex guidelines from different funding sources [7]. Due to more complex projects, it is necessary to find suitable tools [6]. Project management software tools, also called project management information systems (PMIS) are one of the most used tools in today's business environment [8] due to the conclusion of effective project management [9] and their strong correlation to project success [10]. Therefore, a project management software is thought to be introduced into the PIA working group to help meet the high requirements of complex projects.

The result of this study will give an answer to the following research question: How does the introduction of a project management software influence the project management of the PIA group project managers? The answer to this question will help to formulate recommendations of action for the future usage of the chosen PMIS. The structure of this paper is as follows: a literature review will show the current state of the art on the topics of project management as well as PMIS. The methodology for this paper will be explained in the third Section. In the fourth Section, the findings of the semi-structured interviews conducted with the project managers before and after the introduction will be presented. Based on the findings of the pre-introduction situation a criteria catalogue will be created to help in the choice of a PMIS. The fifth Section discusses the impact of the PMIS. The evaluation will lead to a recommendation of action concerning the further usage of the PMIS. In a brief conclusion and outlook, the work of the present paper will be summarized.

## 2 State of the Art

### 2.1 Project Management

Since project management methods have a strong correlation with the basic characteristics of projects, it is of high importance to firstly define projects [11]. The Project Management Institute defines a project as a "temporary endeavor undertaken to create a unique product, service, or result" [12]. Thus, projects can be characterized into the three major aspects: temporary, unique and constrained.

Since this paper is concerned with the management of science and research projects, the focus will be on this project type. These projects can be typically characterized as having high risk and high uncertainty due to researching new territory [13]. Since most of the research projects are financed by third-parties, complex guidelines and rules apply, which the universities and research institutions must deal with [7].

To assess whether a project performance is regarded as a success or a failure, the iron triangle is used [14]. The measurement criteria of the iron triangle are cost, time and quality [15]. These are the basic criteria and can be extended to the following questions: Is the project delivered until its due date? Is the project within budget? Does the project achieve the required level of quality? [14]. Since there is a positive relationship between project management practices and project success [16], tools and techniques of project management must be used to have a higher chance of project success [17].

Project management can be characterized as an accumulation of different tools as well as techniques that help in achieving the project's objective [17]. The tools and techniques can also be labeled as processes. These processes are for instance "initiating, planning, executing, controlling and closing" [12]. There are many different project management methods, tools and techniques, which are often used simultaneously [18]. The most common tools are project management software [19].

Other than project success, effective project management also has an impact on performance and on productivity [20], as well as on the organizational effectiveness [21]. Good project management can have a positive impact on an organization, moreover there is a direct correlation of effective project management and project success. Consequently, it is important to invest in project management techniques and tools [15].

### 2.2 Project Management Software Tools

Project management software tools are one of the most used project management tools and widely applied due to their benefits [8]. PMIS can be defined as "comprehensive systems that support the entire life-cycle of projects" [22]. PMIS have become increasingly relevant, especially due to the complex issues project managers must deal with [23]. The usage of PMIS nowadays can even be considered a necessity [10]. Project managers use PMIS to better the management processes and increase the successful operations [24]. They can especially help to make information on the project accessible to all involved team members, particularly in a multi-project environment [23]. Other advantages are better control over projects, improved project scheduling and resource allocation [24]. PMIS are in general advantageous for project managers [25] and organizations due to improvements in efficiency and effectiveness in project management. Since the improvements are not only linked to the management but also to the performance of the project, PMIS can often be directly linked to project success [10].

## 3 Methodology

To evaluate the impact a PMIS has on the project management of the PIA group there will first be an analysis on the pre-introduction situation to characterize the current project management and identify problems as well as understand expectations for a PMIS. Based on the results from the pre-introduction analysis, a PMIS will be selected and implemented during a testing phase with selected project managers of the PIA group. Thereafter, the post-introduction situation will be analyzed regarding the project managers' experiences and the impact the tool had on their project management. For the evaluation of the situations semi-structured interviews conducted before and after the introduction will be evaluated according to the qualitative content analysis.

This analysis method deals with text evaluation in the context of research projects [26]. Material that can be evaluated with this instrument are interview transcripts, material from open questionnaires, focus groups and other [27]. Concerning this paper, the transcripts of semi-structured interviews will be used to gather information. Semi-structured interviews are especially useful to learn more about opinions as well as diverse experiences [28]. Consequently, they will be used in the present paper to investigate the pre- and post-introduction situation. Prior to the interview a guide will be created forming the basis for the interviews [29].

In the present study, four team members of the PIA group participated in the interviews, which lasted approximately 30 minutes. The most important criteria for the selected participants were their experiences with project management. The most important information on the personas is summarized in Table 1.

**Table 1.** Characteristics of the participants

| Participants | Characteristics |
|---|---|
| Early Career Researcher | End-user perspective, perspective of a member in a project |
| Experienced Project Manager 1 | End-user perspective, high experience in project management |
| Experienced Project Manager 2 | End-user perspective, high experience in project management |
| Head of the Group | Overall perspective, multi-project management |

# 4 Findings

## 4.1 Pre-introduction Situation

All project managers administer several projects at the same time, this amounts to a total of 10–25 projects that the head of the group must keep an overview on. Projects in the PIA group usually last three years. They are mostly third-party funded and have a fixed start and end date. The goals of the projects are defined in the project proposal, which are all unique due to the different research topics.

While analyzing the current project management approach, it became apparent that the head of the group and the experienced project manager 1 are working rather structured and claimed to have a good overview over the projects, whereas the other participants have a rather unstructured approach, often leading to a loss of overview. Among the participants, different working styles can be seen. One of the tools the interviewees use most often is the calendar of their E-Mail-program to enter deadlines for deliverables and reports. Another tool often used to keep an overview of the projects is Microsoft Excel. However, the excel sheets are often not synchronized between involved project members. The interviewees claim that this is not an optimal solution.

In the analysis, several problem areas could be identified. Communication was often deemed critical and very important for the success of projects. Poor communication is often a part of many problems, while successful communication is key to solving many problems. Some of the project managers claim that keeping an overview is often problematic, especially with multiple projects. This is also apparent in the project managers approaches. The experienced project manager 2 and the early career researcher name their own project management as being not optimal since it is rather uncoordinated which can be problematic with managing multiple projects.

Regarding the introduction of a PMIS, most of the project managers claim that it is necessary or becoming more necessary with the increasing complexity of projects. All participants are especially looking forward to a central system that will help with keeping an overview and communication since this will allow everyone to check on the projects instantly without having to prior consult on the current project statuses. For most of the project managers, the functions they wish to see in a PMIS concern keeping an overview of the project and seeing the daily tasks. Keeping everything centralized in one system is very important as well.

### 4.2 Selection and Introduction of a Project Management Software Tool

The availability of PMIS on the markets is increasing at a rapid pace. Consequently, it can be hard to choose a suitable tool [9]. Some PMIS are rather cheap and conclude limited functions. More expensive PMIS on the other side infer more sophisticated functions [30]. To find the most suitable tool for the PIA working group, several steps were taken. At first a criteria catalogue was created according to the needs of the PIA group. The criteria catalogue can also be assessed in Table 2.

**Table 2.** Criteria catalogue

| No. | Criteria |
|---|---|
| 1 | Create new projects |
| 2 | Divide projects in different tasks |
| 3 | Determine relationships and dependencies between subtasks |
| 4 | Observe projects in different perspectives |
| 5 | Ability to update status and progress for the team members |
| 6 | Multi-project management |
| 7 | Hosting the tool in the KIT network |
| 8 | One-off payment |

In a first step, general research on available PMIS was conducted, using websites and blogs as references. In a next step, the list of possible PMIS was reduced by assessing the criteria catalogue. A brief look into the tools' websites helped to greatly diminish the number of possible options. After all of these tools were assessed regarding their features and abilities, Microsoft Project was chosen with the advantages of easily obtaining the licenses due to the KIT having existing license contracts with Microsoft. Selecting another tool was not feasible due to the fact that not all required criteria could be met as well as the difficulty to obtain them and adhere to internal guidelines.

Microsoft Project is one of the most common tools used as a PMIS in many organizations [31]. With the possibility of managing simple and complex projects, the tool offers many functions [30]. Depending on the licenses, more complex features are available. Microsoft Project can be considered as being rather expensive as licenses must be purchased for each team member and on an annual basis [31]. The below average market prices for educational institutions such as the KIT, are still substantial. Depending on the license plans the costs for all PIA team members will range from 850€ to 1500€ per year.

As soon as the licenses were available, the testing phase started. In short training sessions, the project managers were taught the basic functions of Microsoft Project and advised how to implement their projects. The testing project managers were then advised to use the tool for their normal work routine within the projects and to continuously update the progress of their projects.

### 4.3 Post-introduction Situation

During the testing phase, the participants used Microsoft Project several times a week. Using the tool more often was not necessary since there were no deadlines or tasks that had an immediate due date. Moreover, most of the project managers were not used to integrating the tool in their daily workflow yet. All the interviewees mainly used Microsoft Project to get an overview of their project. Regarding the user interface the head of the group, the early career researcher and experienced project manager 2 were rather pleased with the design and thought it provided a good overview. The experienced project manager 1 on the other hand did find the display and clarity satisfying.

In the analysis of the tool's impact, it was apparent that the project managers did not have enough time to notice significant impacts in their project management. The reason for this is the relatively short testing phase of two months due to the limited time frame of this paper. Consequently, most of the opinions on the tool's impact concern the potential impact based on the experience the project managers had so far.

Regarding the communication and collaboration, the interviewees were not able to notice differences. However, all testing project managers feel that it has the potential to positively impact the collaboration and communication since it provides a good overview for the other team members that work on the projects and the head of the group. Especially, the standardized layout and reporting requirements in Microsoft Project ease the issues of overview keeping and reduction of individual status inquiries.

Another problem area, identified, was keeping an overview of the project. All interviewees state that Microsoft Project helped in gaining a better overview over their projects. Especially the experienced project manager 2 and the early career researcher who had a rather unstructured approach to project management and had problems with keeping an overview, noticed improvements. The early career researcher thought Microsoft Project helped a lot in giving structure to his work, since he was able to quickly see what tasks are due and in what priority they must be done. The experienced project managers however thought there was no impact on the structuring or the prioritizing.

Concerning the impact on their daily work, the interviewees did not see a big difference. The main reasons for this are that it is not part of the routine yet and that the other team members cannot use the tool for their respective projects yet. Consequently, all the interviewees claimed that the tool generates more work instead of simplifying their daily workday, which is mostly due to the transition period.

The interviewees have not been able to sense changes in their productivity so far. Nonetheless all project managers as well as the head of the group can see the potential of an improvement in the productivity as well as the efficiency.

Regarding the impact the tool had on the projects, the interviewees agreed that the testing phase of two months was too short to learn about improvements. However, the experienced project manager 2 claimed that one project was positively impacted due to having a better overview and better control. Moreover, all interviewees believe that the tool can impact the projects in the long run. Most of them see the potential of improvements in time management and quality of work due to better communication, with the head of the group and other project managers. In Table 3 the noticed impacts and potential impacts of the tool are summarized.

**Table 3.** Impact of Microsoft Project

| Impact area | Have there been improvements? | Is there the potential for an improvement? |
|---|---|---|
| Communication | No | Yes |
| Keeping an Overview | Yes | Yes |
| Structure | Yes and No | Yes |
| Daily Work | No | Yes |
| Productivity and Efficiency | No | Yes |
| Projects | Yes and No | Yes |

The expectations of the interviewees were partially fulfilled with the implementation of Microsoft Project. Advantages the interviewees named are the opportunity to portray the whole project. This is positive for the other team members and helps with meeting deadlines and structuring the tasks. These advantages conclude transparency, which can help when being new to a project and needing information. Most of the interviewees named the integration of Microsoft Project in Microsoft Teams as an advantage since this made the usage easier for them. Although there are many advantages, the interviewees also named disadvantages, especially the experienced project managers. They claimed that it was complicated to create projects in a detailed manner, including dependencies of tasks. Another disadvantage they named is that Microsoft Project creates another workplace instead of creating a central system.

Concerning the implementation of Microsoft Project in the PIA group, all interviewees agree on the fact that the tool would positively impact the projects' success and project management experience in the long run. However, the experienced project managers share the concerns of the tool not being accepted. They claim that there would have to be an obligation to use the tool, since the tool is most likely to impact the project management positively, when all team members are using it continuously.

## 5 Discussion

The comparison of the situation before and after the introduction shows that there was an impact from the use of Microsoft Project. However, most improvements were not significant due to the short testing time. Nonetheless, all testing project managers see the potential for improvements in the identified problem areas. Moreover, all saw great benefits in keeping an overview and the early career researcher noticed improvements in the structuring of his work. It was apparent that the project managers that had a rather unstructured approach noticed greater improvements in gaining an overview and structuring tasks. Consequently, the project managers see potential for improvements or have already experienced minor impacts in all impact areas identified in the state of the art. Regarding the expectations towards a PMIS, most of them were fulfilled. The same applies for the advantages and disadvantages of the tool. Although the tool provides a better overview, transparency for all team members, simple usage and has the potential to impact many problem areas, there are still missing functions and some inconveniences for the project managers when using the tool. Nonetheless, the impact the tool already has on keeping an overview and the advantages associated with it are promising for the further usage. The PMIS can help in sustaining the productivity of the project managers and help to reduce their project management efforts and time put into their work. Hence, it could provoke sustainable effects on the project management in the future. Because of this, the usage of Microsoft Project should be continued in the future.

All in all, the tool impacted the project management positively in some areas and has the potential to positively influence the project management and project success in the long run. Regarding the further usage, the recommendation of action is to continue using the tool to see how it affects the project management for a longer time.

## 6 Conclusion

This paper was able to show the problem areas existing in the investigated research group related to project management, the importance for the introduction of a PMIS and how the implementation has impacted the project management. From this, a recommendation of action could be derived regarding the future usage.

At the beginning, the state of the art emphasized the importance of effective project management as well as project management tools. Moreover, the literature review states that PMIS are one of the most used tools nowadays. In an analysis of the pre-introduction situation, various problem areas were identified and the importance of the introduction of a PMIS emphasized. The selection of a suitable project management software was then influenced by the findings of the analysis and a criteria catalogue. After Microsoft Project was implemented, a testing phase began. The analysis of the post-introduction situation has shown that there were impacts. All project managers were able to notice great improvements in keeping an overview of their projects. Furthermore, all emphasized that a substantial impact could be made in all areas.

With a comparison of the situation before and after the introduction, an answer to the research question could be given. As a result, it can be stated that the tool positively impacted some areas of the project management. Moreover, all project managers agree that the tool can further improve other areas, in which they have not noticed an impact yet. Because of the benefits, it can be said that Microsoft Project should be used further in research groups. Particularly due to the possibility to change the project management sustainably and reduce time and effort for the project managers.

Although the results of this thesis show that Microsoft Project will benefit and impact the project management and project success positively, there are some limitations that must be considered concerning the expressiveness of the results. Due to the short testing time most project managers did not have enough time to properly integrate the tool in their working life. Consequently, most of the results rely on assumptions that are based on the experiences the project managers made so far. It would have been more promising if all team members would have tested the tool since it would have allowed more in-depth results regarding the impact and the acceptance. Moreover, different personas evoke different testing experiences, which leads to a lack of generalizability of this study. In conclusion, future work should assess the situation after using the tool with all team members. Nonetheless, in this study the impact of the tool has been assessed to some extent and an answer to the research question has been found.

**Acknowledgements.** This work was carried out with the support of the Karlsruhe Nano Micro Facility (KNMFi, www.knmf.kit.edu), a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu) and under the Helmholtz Research Programme STN (Science and Technology of Nanosystems) at KIT.

## References

1. KIT. https://www.kit.edu/kit/index.php. Last Accessed 30 June 2021
2. KIT. https://www.kit.edu/kit/institute.php. Last Accessed 30 June 2021
3. KIT. https://www.kit.edu/themen/index.php. Last Accessed 30 June 2021
4. KIT. https://www.iai.kit.edu/index.php. Last Accessed 30 June 2021
5. KIT. https://www.iai.kit.edu/english/groups_478.php. Last Accessed 1 July 2021
6. Ng, J.J.: Understanding project management directions from project management trends. IEEE Eng. Manage. Rev. **47**(2), 128–132 (2019)
7. Gröger, S., Schumann, M.: Managing third-party funding projects at German state universities—a theoretical deduction of design principles for implementing an IT-artifact. In: Twenty Second European Conference on Information Systems, pp. 1–15 (2014)
8. Fereira, T., Gutiérrez-Artacho, J., Bernardino, J.: Freemium project management tools: Asana, Freedcamp and Ace Project. In: World Conference on Information Systems and Technologies, pp. 1026–1037 (2018)
9. Cicibas, H., Unal, O., Demir, K.A.: A comparison of project management software tools (PMST). In: Software Engineering Research and Practice, pp. 560–565 (2010)
10. Raymond, L., Bergeron, F.: Project management information systems: an empirical study of their impact on project managers and project success. Int. J. Project Manage. **26**(2), 213–220 (2008)

11. Madauss, B.J.: Projektmanagement - Theorie und Praxis aus einer Hand, 8th edn. Springer, Berlin (2020)
12. Project Management Institute: A Guide to the Project Management Body of Knowledge (PMBOK Guide), Newton Square (2013)
13. Youker, R.: The difference between different types of projects. PM World J. **6**(4), 1–8 (2017)
14. Pollack, J., Helm, J., Adler, D.: What is the Iron Triangle, and how has it changed? Int. J. Manag. Proj. Bus. **11**(2), 527–547 (2018)
15. Atkinson, R.: Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria. Int. J. Project Manage. **17**(6), 337–342 (1999)
16. Radujković, M., Sjekavica, M.: Project management success factors. Procedia Eng. **196**, 607–615 (2017)
17. Attarzadeh, I., Ow, S.H.: Project management practices: the criteria for success or failure. Commun. IBIMA **1**(28), 234–241 (2008)
18. White, D., Fortune, J.: Current practice in project management - an empirical study. Int. J. Project Manage. **20**(1), 1–11 (2002)
19. Liberatore, M.J., Pollack-Johnson, B.: Factors influencing the usage and selection of project management software. IEEE Trans. Eng. Manage. **50**(3), 164–174 (2003)
20. Abbasi, G.Y., Al-Mharmah, H.A.: Project management practice by the public sector in a developing country. Int. J. Project Manage. **18**(2), 105–109 (2000)
21. Shenhar, A.J., Dvir, D., Levy, O., Maltz, A.C.: Project success: a multidimensional strategic concept. Long Range Plan. **34**(6), 699–725 (2001)
22. Ahlemann, F.: Towards a conceptual reference model for project management information systems. Int. J. Project Manage. **27**(1), 19–30 (2009)
23. Mishra, A., Mishra, D.: Software project management tools: a brief comparative view. ACM SIGSOFT Softw. Eng. Notes **38**(3), 1–4 (2013)
24. Bondarenko, S., Lagodienko, V., Sedikova, I., Kalaman, O.: Application of project analysis software in project management in the pre-investment phase. Int. J. Mech. Eng. Technol. **9**(13), 676–684 (2018)
25. Caniëls, M.C.J., Bakens, R.J.J.M.: The effects of Project Management Information System on decision making in a multi project environment. Int. J. Project Manage. **30**(2), 162–175 (2012)
26. Mayring, P., Fenzl, T.: Qualitative Inhaltsanalyse. Springer Fachmedien, Wiesbaden (2019)
27. Mayring, P.: Qualitative content analysis: theoretical foundation, basic procedures and software solution, Gesis, Klagenfurt (2014)
28. Longhurst, R.: Semi-structured interviews and focus groups. Key Methods Geogr. **3**(2), 143–156 (2003)
29. Luo, L., Wildemuth, B.M.: Semistructured interviews. In: Applications of Social Research Methods to Questions in Information and Library Science, 2nd edn. Libraries Unlimited, Santa Barbara (2017)
30. Kostalova, J., Tetrevova, L., Svedik, J.: Support of project management methods by project management information system. Procedia Soc. Behav. Sci. **210**, 96–104 (2015)
31. Desmond, C.: Project management tools - software tools. IEEE Eng. Manage. Rev. **45**(4), 24–25 (2017)

# A Genetic Algorithm for the Dynamic Management of Cellular Reconfigurable Manufacturing Systems

Janine Tatjana Maier[1](✉), Matthias Schmidt[1], Francesco Gabriele Galizia[2], Marco Bortolini[2], and Emilio Ferrari[2]

[1] Institute of Product and Process Innovation, Leuphana University of Lüneburg, Universitätsallee 1, 21335 Lüneburg, Germany
{janine_tatjana.maier,matthias.schmidt}@leuphana.de
[2] Department of Industrial Engineering, Alma Mater Studiorum - University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy
{francesco.galizia3,marco.bortolini3,emilio.ferrari}@unibo.it

**Abstract.** Globalization and rapid technological changes have led to increased customer requirements and an intensified competition. To remain cost-efficient, manufacturing companies move from traditional manufacturing systems towards flexible manufacturing systems. Reconfigurable manufacturing systems have proven to be an effective way of adapting to the rapidly changing market conditions. Although, an increasing interest in this topic is visible in academics and industrial practice, the research is still limited. From an industrial point of view, a fast and easy adaptable solution for managing such a system dynamically is required. Based on an optimization model, a genetic algorithm for the dynamic management of cellular reconfigurable manufacturing systems was developed. A case study shows the effects of varying the selection method, the crossover operator, and the values for the occurrence of crossover and mutation processes. The application of the genetic algorithm resulted in an improvement of around 3% compared to the best solution of the initial population. Random selection showed the best results in the respective case. Nevertheless, it can be assumed that this selection method is outperformed by others as the number of generations increases.

**Keywords:** Reconfigurable manufacturing · Genetic algorithm · Selection · Crossover · Mutation · Parameter variation

## 1 Introduction

Sustainability is increasing important for customers and thus sustainable manufacturing has become a core value of various companies [1]. Regarding sustainable manufacturing a distinction between the four strategies waste minimization, material efficiency, resource efficiency, and eco-efficiency can be made [2]. As materials and energy are becoming less abundant a re-thinking of manufacturing systems is visible.


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 21–32, 2023.
https://doi.org/10.1007/978-981-19-9205-6_3

Flexibility and changeability are crucial to remain competitive in the context of uncertainty in product demand, short product life-cycles, product portfolio diversity, expanding customer services and advanced production structures [3]. The manufacturing system is a key aspect for adapting to the rapidly changing market conditions while avoiding significant losses in productivity [4]. According to literature, a reconfigurable manufacturing system (RMS) is one of the most suitable solutions to achieve flexibility [5]. The design of RMSs follows the six core characteristics scalability, convertibility, diagnosability, customization, modularity and integrability [6]. As RMSs can be continuously changed and upgraded, they can be used throughout various industries [7] and are frequently labelled as the manufacturing paradigm of the future [3]. RMSs are typically arranged in a cellular production pattern which includes a set of reconfigurable machine cells (RMCs) [8]. RMCs contain reconfigurable machine tools (RMTs), which can perform various tasks through a set of auxiliary modules. The number of feasible tasks increases with the number of auxiliary modules [9]. As the amount of available auxiliary module units is limited, the assignment of these modules provides a challenge for companies. To produce as economical as possible, the total time required needs to be minimized while satisfying a variety of constraints regarding the placement and the flow of the auxiliary modules and the products. The importance and the complexity of the topic is shown by the existing amount of approaches addressing the design and management of RMSs as well as the optimization of the use of auxiliary modules [10].

This paper presents a genetic algorithm (GA) for the dynamic management of cellular reconfigurable manufacturing systems. The subsequent Sect. 2 outlines the optimization model, which provided the framework for the development of the respective GA. The core elements of the algorithm are addressed in Sect. 3. A case study is presented in Sect. 4 to show the practicality of the approach and to provide first insights based on a parameter variation. In Sect. 5, the conclusions of the paper are summarized and future research possibilities are outlined.

## 2 Model Description

Bortolini et al. developed a linear programming model to optimize the dynamic management of RMSs [11]. It aims to minimize the total time $\Omega$ required for installation, disassembly and travel processes while fulfilling various constraints such as the availability of the auxiliary modules. The list of indices, parameters and decision variables characterizing the objective function is in Table 1.

$$\begin{aligned}\min \Omega = &\sum_{t=1}^{T}\sum_{m=1}^{Z}\sum_{h=1}^{H} X_{mht} \cdot \left(\sum_{k=1}^{K} \lambda_{mk} \cdot A_{hk}\right) \\ &+ \sum_{t=1}^{T}\sum_{m=1}^{Z}\sum_{h=1}^{H} Y_{mht} \cdot \left(\sum_{k=1}^{K} \mu_{mk} \cdot A_{hk}\right) \\ &+ \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{j_1=1}^{N}\sum_{t=1}^{T-1} F_{ijj_1t} \cdot t_{ijj_1t} + \sum_{h=1}^{H}\sum_{j=1}^{N}\sum_{j_1=1}^{N}\sum_{t=1}^{T-1} D_{hjj_1t} \cdot \left(\sum_{k=1}^{K} Z_{kjj_1} \cdot A_{hk}\right)\end{aligned} \tag{1}$$

**Table 1.** Indices, parameters and decision variables of the objective function

| Symbol | Explanation |
|---|---|
| $i$ | products, i = 1,…, M |
| $j$ | RMCs, j = 1,…, N |
| $m$ | RMTs, m = 1,…, Z |
| $k$ | auxiliary module types, k = 1,…, K |
| $h$ | auxiliary modules, h = 1,…, H |
| $t$ | counter for periods, t = 1,…, T |
| $A_{hk}$ | 1 if auxiliary module h is of type k; 0 otherwise [binary] |
| $t_{ijj1}$ | inter-cell travel time to move the batch of product i from RMC j to RMC j1 [min/ batch] |
| $Z_{kjj1}$ | travel time for auxiliary module type k from RMC j to RMC j1 [min/module] |
| $\lambda_{mk}$ | installation time of module type k on RMT m [min/module] |
| $\mu_{mk}$ | time to disassemble a module type k from RMT m [min/module] |
| $F_{ijj1t}$ | 1 if a batch of product i flows from RMC j to RMC j1 in period t; 0 otherwise [binary] |
| $D_{hjj1t}$ | 1 if auxiliary module h moves from RMC j to RMC j1 in period t; 0 otherwise [binary] |
| $V_{mht}$ | 1 if module h is on RMT m in period t; 0 otherwise [binary] |
| $X_{mht}$ | 1 if module h is installed on RMT m in period t, 0 otherwise [binary] |
| $Y_{mht}$ | 1 if RMT m disassembles module h in period t, 0 otherwise [binary] |

Although the computation time of the case study presented by the Authors was low, they point out the importance of exploring heuristic and meta-heuristic methods. In industrial practice, time pressure is high and the majority of companies has no specialists dedicated to solving such a task. Taking into account the dynamic environment of manufacturing companies, fast decisions and their continuous re-evaluation are required. The Covid-19 pandemic has highlighted these needs even more [12]. As optimization models neglect the numerous unpredictable influencing factors existing in industrial practice, a calculated exact solution might not be optimal. As the model complexity increases and the data sets become larger, heuristic and meta-heuristic methods can provide sufficient solutions in a reasonable amount of time. From an industrial point of view, heuristic methods are more practical than an exact algorithm.

As a first step in this direction, Bortolini et al. created a GA using a simplified version of their model [13]. The practicality of the general idea is shown. By comparing eighteen scenarios first insights on the performance of the GA regarding the parameter variation are gained. For simplicity, the number of auxiliary module units per RMT is limited and the total number of units is undefined. The case study is based on a rather small data set including only five products. To reflect the complexity in industrial practice a combination of the two approaches addressed above is required.

# 3 Genetic Algorithm

## 3.1 Solving Procedure

A GA is a non-deterministic stochastic search method, which mimics the natural evaluation process for solving problems within a complex solution space [14]. Chromosomes represent solutions in a binary string format, which are continuously changed by the biological-inspired operators selection, crossover and mutation until the termination criterion is reached. The fitness of a solution equals its fit to solve the respective problem. GAs are used across various domains [15]. Regarding production planning and control tasks, GAs are mainly applied for scheduling [16] and inventory control [17]. Various Authors have proven the fit of a GA in the context of RMS. For example, Dou et al. developed a set of economical single-product flow-line configurations for a multi-product RMS [18]. Whereas, Abbasi and Houshmand generated a GA to determine the optimal sequence of production tasks corresponding to batch sizes and configurations of selected product families [19]. For the respective problem addressed in this paper, all the decision variables of the objective function (Eq. 1) can be derived from the binary string $W_{mit}$, which describes the RMT on which each product is produced in each period. Nevertheless, there are multiple possible ways to place the auxiliary modules on the RMTs. Following standard literature [8, 9], the following assumptions were made for the GA presented in this paper:

- The product work cycle and the compatibilities among tasks, RMTs and auxiliary modules are known.
- The processing, travel and reconfiguration times are given.
- As soon as a batch of a product is finished a new one is started.
- A limited number of and auxiliary module types and units per type exist.
- At the end of each period, all product batches move to the next task according to their work cycle.
- All auxiliary module units must be installed in the first period.
- If an auxiliary module unit is not required in the first period, it will be installed on the RMT it is required on next.
- If an auxiliary module unit is not required in a period, it remains on the RMT on which it was required last.
- If different auxiliary module types are possible to fulfill a task, it is checked if one of them is already located on the respective RMT. In case multiple options are possible, the RMT which requires the lowest sum of installation, disassembly and auxiliary module travel time is chosen. In case of equality, the selection of the RMT is random.
- If an auxiliary module unit is required on a different RMT than in the previous period, it is disassembled from the previous RMT and installed on the current one in the period in which the change occurs.
- If an auxiliary module unit is not required during all periods, it is installed on the RMT which requires the lowest sum of installation and disassembly time in the first period. In case of equality, the selection of the RMT is random.
- In the last period all auxiliary module units must be disassembled.

### 3.2 Parameters for Variation

Numerous variations of the parameters of GAs exist and continuously new ones are developed [20]. To achieve a global optimum in a time effective manner, a balance between selection pressure and genetic diversity is required. Selection methods which consider the fit of the individual solutions increase the selection pressure but decrease the diversity. In case a significant proportion of the population is taken by an extraordinary individual an undesirable convergence can occur. A detailed comprehensive comparison of convergence handling approaches is provided by Pandey et al. [21]. Commonly used selection methods are random, roulette wheel, elitism and tournament. According to Shukla et al. tournament selection outperforms other selection methods in terms of complexity and convergence rate [15]. Nevertheless, the most suitable selection method depends highly on specific optimization problem. In addition, various other aspects such as the operators for crossover, the crossover and mutation rates and the handling of new solutions have a high impact on the fit of the individual solutions and the evolution of the population. One point, two point and uniform are the main applied crossover operators. Most of the studies combines high crossover rates with low mutation rates [22]. The solutions gained by the GA can be either added to the previous population or can replace previous solutions based on their fit.

## 4 Case Study

### 4.1 Data Set and Experimental Runs

The GA introduced and described in Sect. 3 is applied to a case study representative of an operative industrial company in the manufacturing sector. Observing 20 products combined with 5 RMTs available to process them for 24 time periods results in 2400 binary values for each solution $W_{mit}$. As each product must be assigned to exactly one RMT, the value of 480 alleles of a possible solution must be 1 while the value of the remaining alleles is 0. In total 15 different tasks needing between 1 and 3 different auxiliary module types depending on the selected RMTs exist. The various constraints such as the maximum of 20 auxiliary module units equally assigned to 5 different auxiliary module types and the duration of 500 minutes per time period limit the solution space. Each RMT is assigned to one RMC, i.e., RMT #1 in RMC #1, RMT #2 in RMC #2, RMT #3 in RMC #3, RMT #4 in RMC #4 and RMT #5 in RMC #5. Besides the inter-cell travel times per batch and per auxiliary module, the unitary processing times, the installation and disassembly times of the available auxiliary module types, the batch sizes and work cycles for the products are taken from Bortolini et al. [11].

A Microsoft Excel software tool was created to validate and implement the GA. Visual Basic for Applications (VBA) was chosen as programming language. VBA is widely used in industrial practice and academics as it enables an easy import and maintenance of data. In additional, the numerous free of charge existing VBA procedures can be adapted without a high level of programming skills. To determine a suitable number of generations, initial experimental runs were required.

After 100 generations, the results of the exemplary chosen parameter combinations differentiated enough to draw first conclusions regarding the performance. Random selection was included in the study as a baseline for the comparison. To examine the effects of selection pressure and genetic diversity tournament selection and the elitism method linear rank selection were considered. The tournament size was set to two as it is directly related to the probability of loss of diversity [15]. Roulette wheel selection was excluded as it increases the selection pressure drastically and has combined with a low mutation rate a high risk of reaching an undesirable convergence. Each feasible solution was added to the solution space instead of only keeping the solutions with the highest fitness. This decreases the selection pressure but at the same time avoids losing diversity. In this particular case, the components of each binary string $W_{mit}$ are interrelated, thus uniform crossovers resulted in a very low number of feasible solutions regardless of the selection method. Thus, uniform crossovers were excluded from the study. One point crossovers showed a slightly higher number of feasible solutions than two point crossovers. As this is not directly related to the fit of the solutions, both crossover operators were selected for an in-depth analysis. Following the standard literature [13, 22, 23], high crossover rates and low mutations rate, namely crossover rates of 92%, 95%, 98% and mutations rates of 0.0001% and 0.0002%, were set.

It should be noted that these exact numbers were chosen based on the initial runs for the described data set. Therefore, they can be used as starting points for the analysis for similar other problems but should be re-evaluated and individually adjusted for each data set. To compensate for the very low mutation rates which were necessary due to the interrelations of $W_{mit}$, the starting solutions (fitness values: 5406.06; 5769.89; 5809.41; 5829.46) were manually selected ensuring every component for all feasible solution is already included within them. This provided the opportunity to reach every possible solution only by crossover while maintaining a high number of feasible solution per experimental run and a low risk of spending a long time within a local optima. Combining the described parameters led to a set of 36 experimental runs.

### 4.2 Results and Discussion

The different parameter combinations resulted in between 50 and 137 feasible solutions per 100 generations (Table 2). The lowest fitness value was achieved by combining random selection with a two point crossover, a crossover rate of 98% and a mutation rate of 0.0001% (experimental run 11). This equals an improvement of around 3% compared to the best solution of the initial population. Nevertheless, the same run includes solutions with fitness values which highly exceed the values of the starting solutions. It contains a total of 74 feasible solutions, which equals only 35% of the total amount of possible new solutions. Linear rank selection combined with a two point crossover, a crossover rate of 92% and a mutation rate of 0.0001% led to the least suitable results (experimental run 19). The respective run resulted in the highest standard deviation. The two runs containing the highest average fitness and median of the fitness values also combine linear rank selection with a two point crossover. As these values highly exceed the values of the starting solutions, these particular combinations do not seem suitable to solve the respective problem.

**Table 2.** Results of the experimental runs

| Experimental run *Selection method (random (r); linear rank (l); tournament (t)); Crossover operator; Crossover rate; Mutation rate* | Feasible solutions | Lowest | Highest | Average | Median | Standard deviation |
|---|---|---|---|---|---|---|
| 1 *(r; one point; 92; 0.0001)* | 123 | 5386.99 | 5860.39 | 5715.72 | 5796.83 | 167.93 |
| 2 *(r; one point; 92; 0.0002)* | 99 | 5406.06 | 5847.28 | 5741.03 | 5791.59 | 135.52 |
| 3 *(r; one point; 95; 0.0001)* | 134 | 5398.40 | 5829.46 | 5657.01 | 5781.05 | 179.44 |
| 4 *(r; one point; 95; 0.0002)* | 104 | 5402.08 | 5866.98 | 5767.29 | 5791.42 | 101.57 |
| 5 *(r; one point; 98; 0.0001)* | 137 | 5398.40 | 5854.78 | 5623.79 | 5723.45 | 187.90 |
| 6 *(r; one point; 98; 0.0002)* | 103 | 5393.97 | 5968.87 | 5711.62 | 5783.89 | 178.68 |
| 7 *(r; two point; 92; 0.0001)* | 108 | 5406.06 | 5947.58 | 5803.13 | 5802.35 | 91.37 |
| 8 *(r; two point; 92; 0.0002)* | 90 | 5406.06 | 5936.24 | 5811.30 | 5822.21 | 89.18 |
| 9 *(r; two point; 95; 0.0001)* | 75 | 5391.45 | 6015.46 | 5783.40 | 5808.46 | 151.06 |
| 10 *(r; two point; 95; 0.0002)* | 52 | 5395.37 | 6012.59 | 5777.49 | 5791.50 | 138.00 |
| 11 *(r; two point; 98; 0.0001)* | 74 | 5253.93 | 6102.84 | 5777.02 | 5811.39 | 172.40 |
| 12 *(r; two point; 98; 0.0002)* | 50 | 5281.28 | 6185.46 | 5751.53 | 5793.47 | 168.17 |
| 13 *(l; one point; 92; 0.0001)* | 123 | 5406.06 | 5860.39 | 5791.91 | 5800.16 | 71.55 |
| 14 *(l; one point; 92; 0.0002)* | 99 | 5406.06 | 5860.03 | 5803.15 | 5813.09 | 70.70 |
| 15 *(l; one point; 95; 0.0001)* | 134 | 5399.76 | 5851.41 | 5798.35 | 5820.23 | 89.58 |

(*continued*)

**Table 2.** (*continued*)

| Experimental run *Selection method (random (r); linear rank (l); tournament (t)); Crossover operator; Crossover rate; Mutation rate* | Feasible solutions | Lowest | Highest | Average | Median | Standard deviation |
|---|---|---|---|---|---|---|
| 16 *(l; one point; 95; 0.0002)* | 104 | 5406.06 | 5866.98 | 5797.73 | 5806.22 | 67.17 |
| 17 *(l; one point; 98; 0.0001)* | 137 | 5399.76 | 5854.78 | 5798.94 | 5819.82 | 88.69 |
| 18 *(l; one point; 98; 0.0002)* | 103 | 5406.06 | 5888.01 | 5789.94 | 5809.41 | 93.40 |
| 19 *(l; two point; 92; 0.0001)* | 95 | 5406.06 | 6361.50 | 5982.96 | 5988.95 | 189.15 |
| 20 *(l; two point; 92; 0.0002)* | 85 | 5406.06 | 6225.91 | 5970.04 | 5993.18 | 115.32 |
| 21 *(l; two point; 95; 0.0001)* | 99 | 5406.06 | 6288.94 | 6010.42 | 6039.84 | 148.44 |
| 22 *(l; two point; 95; 0.0002)* | 84 | 5406.06 | 6186.13 | 5956.26 | 5980.08 | 134.49 |
| 23 *(l; two point; 98; 0.0001)* | 112 | 5406.06 | 6258.00 | 6011.40 | 6034.11 | 134.98 |
| 24 *(l; two point; 98; 0.0002)* | 87 | 5406.06 | 6186.13 | 5958.45 | 5980.75 | 131.29 |
| 25 *(t; one point; 92; 0.0001)* | 124 | 5406.06 | 5864.35 | 5817.23 | 5822.41 | 40.98 |
| 26 *(t; one point; 92; 0.0002)* | 109 | 5406.06 | 5866.87 | 5814.56 | 5820.14 | 44.94 |
| 27 *(t; one point; 95; 0.0001)* | 124 | 5406.06 | 5864.35 | 5817.23 | 5822.41 | 40.98 |
| 28 *(t; one point; 95; 0.0002)* | 111 | 5406.06 | 5854.41 | 5813.65 | 5822.70 | 57.38 |
| 29 *(t; one point; 98; 0.0001)* | 133 | 5406.06 | 5861.15 | 5817.39 | 5821.15 | 39.83 |
| 30 *(t; one point; 98; 0.0002)* | 102 | 5406.06 | 5853.74 | 5814.23 | 5819.04 | 44.65 |

(*continued*)

**Table 2.** (*continued*)

| Experimental run *Selection method (random (r); linear rank (l); tournament (t)); Crossover operator; Crossover rate; Mutation rate* | Feasible solutions | Lowest | Highest | Average | Median | Standard deviation |
|---|---|---|---|---|---|---|
| 31 *(t; two point; 92; 0.0001)* | 98 | 5406.06 | 6095.89 | 5880.08 | 5873.81 | 76.50 |
| 32 *(t; two point; 92; 0.0002)* | 72 | 5406.06 | 6174.40 | 5849.75 | 5851.48 | 101.88 |
| 33 *(t; two point; 95; 0.0001)* | 111 | 5406.06 | 6307.74 | 5928.04 | 5926.53 | 113.51 |
| 34 *(t; two point; 95; 0.0002)* | 84 | 5406.06 | 5978.90 | 5847.22 | 5852.64 | 63.03 |
| 35 *(t; two point; 98; 0.0001)* | 97 | 5406.06 | 6114.80 | 5912.84 | 5896.70 | 100.28 |
| 36 *(t; two point; 98; 0.0002)* | 77 | 5406.06 | 6234.97 | 5891.90 | 5887.56 | 125.02 |

The average fitness as well as the median of the fitness values are similar for all runs. The standard deviation of all runs using random selection and one point crossover is higher than the majority of other runs. In accordance with literature, this leads to the assumption that the random selection will be outperformed by other selection methods as the number of generations increases. The results of all runs using tournament selection are similar (Fig. 1a). None of them achieves a lower fitness than the starting solutions. This can be explained by the small size of the initial population and the resulting high probability to select identical solutions. It can be assumed that the results of the runs will differ more as the size of the population increases along with the number of generations. A mutation rate of 0.0001% outperformed a mutation rate of 0.0002% for all combinations (Fig. 1c). It achieves a lower or a least equal fitness and a higher number of feasible solutions. In most cases the standard deviation is higher, which directly results from the higher number of feasible solutions. Regarding the crossover rate no clear trend could be derived. As the lowest fitness value was achieved by using random selection, the respective parameter combination provides a suitable baseline for the assessment of additional experimental runs. This includes the comparison with linear rank and tournament selection for a higher number of generations and a wider set of crossover and mutation rates.

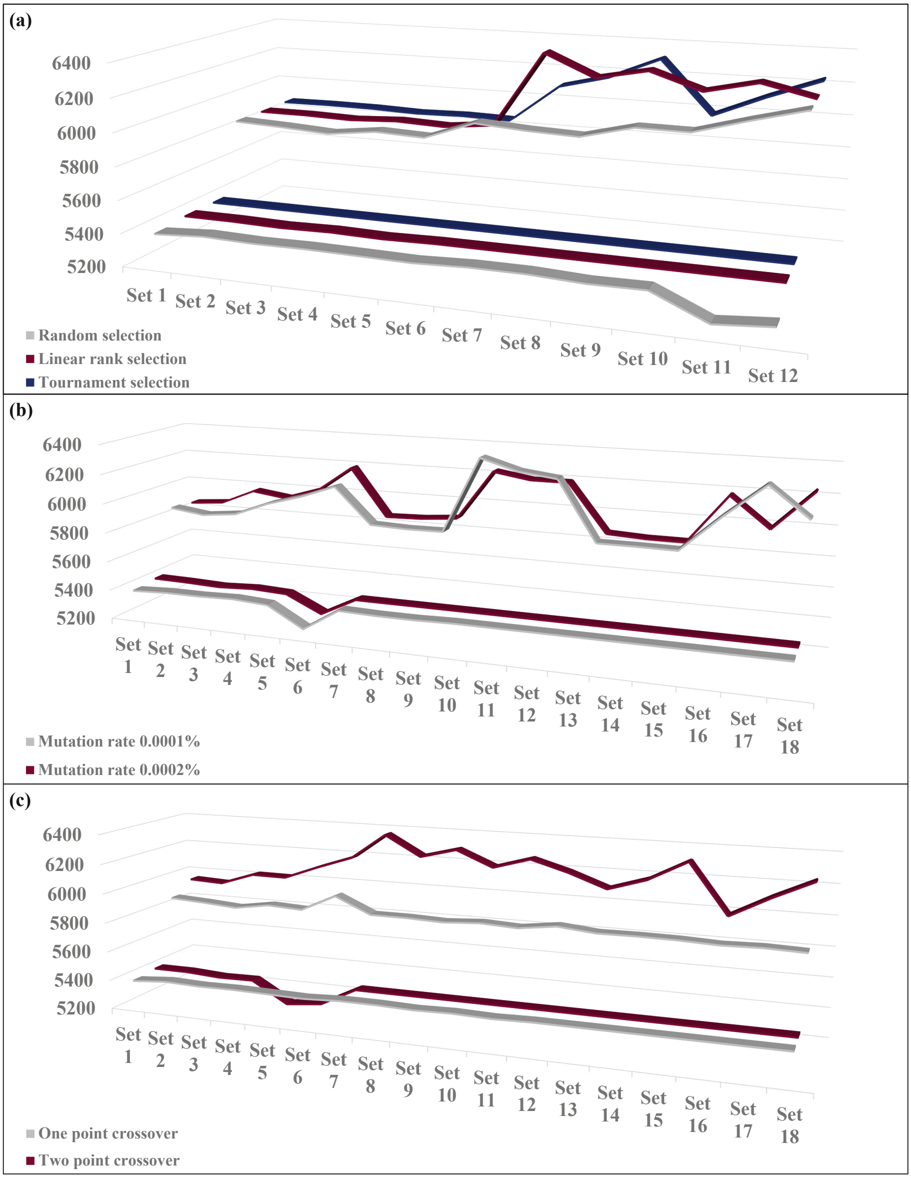



**Fig. 1.** Comparison of the lowest and highest fitness values after 100 generations varying the selection method (a), the crossover operator (b) or the mutation rate (c) while keeping the rest of the parameters stabile

## 5 Conclusions and Outlook

The manufacturing industry faces an increasing complex and dynamic environment as today's customers expect individual products at low prices, but also short and reliable delivery times. At the same time there is an increasing need for sustainable manufacturing. RMSs provide an effective way for manufacturing companies to achieve flexibility and use their resources more efficient. Thus, they can remain competitive in today's dynamic environment. Nevertheless, the research on this topic is still limited. Existing optimization models cannot provide sufficient solutions in a reasonable amount of time considering the large data sets required to reflect industrial practice appropriately. Regarding the numerous unpredictable influencing factors as well as the time pressure existing in industrial practice, heuristic and meta-heuristic methods are more practical than exact algorithms.

In this paper, a GA is presented as a step towards a fast and easy adaptable solution for the dynamic management of such a RMS. A case study shows the practicality of the approach. Varying the selection method, the crossover operator, and the values for the occurrence of crossover and mutation processes resulted in 36 experimental runs. As the number of generations as well as the size of the initial population was kept small, random selection lead to the best results. Even though, a point crossover in combination with the random selection showed better results than a two point crossover, this was not the case regarding linear rank selection (Fig. 1b). These contrary findings should be examined further. A detailed analysis including more parameter combinations is required. Based on this, the most promising parameter combinations should be selected and the number of generations increased to evaluate the derived hypotheses.

The created software tool offers the opportunity to achieve a transparent decision without requiring a high modeling effort. Thus, the tool contributes to the saving of manpower, while the dynamic management of RMS and the developed algorithm support a more efficient use of machines. Analyzing larger data sets could provide interesting insides. To counteract the difficulties arising from the processing of a large amount of data with VBA, the programming language should be switched, for example to Python.

## References

1. Herrmann, C., Schmidt, C., Kurle, D., Blume, S., Thiede, S.: Sustainability in manufacturing and factories of the future. Int. J. Precis. Eng. Manuf. Green Technol. **1**(4), 283–292 (2014). https://doi.org/10.1007/s40684-014-0034-z
2. Abdul Rashid, S.H., Evans, S., Longhurst, P.: A comparison of four sustainable manufacturing strategies. Int. J. Sustain. Eng. **1**(3), 214–229 (2008)
3. Wiendahl, H.-P., et al.: Changeable manufacturing - classification, design and operation. CIRP Annal. Manuf. Technol. **56**(2), 783–809 (2007)
4. Koren, Y.: The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems. Wiley, New York (2010)
5. Yelles-Chaouche, A.R., Gurevsky, E., Brahimi, N., Dolgui, A.: Reconfigurable manufacturing systems from an optimisation perspective: a focused review of literature. Int. J. Prod. Res. **59**(21), 6400–6418 (2020)
6. Koren, Y., Ulsoy, A.G.: Vision, principles and impact of reconfigurable manufacturing systems. Power. Int. **5**(3), 14–21 (2002)

7. Andersen, A.L., Brunoe, T.D., Nielsen, K.: Investigating the potential in reconfigurable manufacturing: a case-study from Danish industry. In: Umeda, S., Nakano, M., Mizuyama, H., Hibino, N., Kiritsis, D., von Cieminski, G. (eds.) Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth. APMS 2015. IFIP Advances in Information and Communication Technology, vol. 459, pp. 274–282. Springer, Cham (2015)
8. Pattanaik, L.M., Jain, P.K., Mehta, N.K.: Cell formation in the presence of reconfigurable machines. Int. J. Adv. Manuf. Technol. **34**, 335–345 (2007)
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. 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)
11. Bortolini, M., Ferrari, E., Galizia, F.G., Regattieri, A.: An optimisation model for the dynamic management of cellular reconfigurable manufacturing systems under auxiliary module availability constraints. J. Manuf. Syst. **58**, 442–451 (2021)
12. Napoleone, A., Pratavieraa, L.B.: Reconfigurable manufacturing: lesson learnt from Covid-19 outbreak. In: Lalic, B., Majstorovic, V., Marjanovic, U., von Cieminski, G., Romero, D. (eds.) Advances in Production Management Systems: The Path to Digital Transformation and Innovation of Production Management Systems. APMS 2020. IFIP Advances in Information and Communication Technology, vol. 591, pp. 457–465. Springer, Cham (2020)
13. Bortolini, M., Cafarella, C., Ferrari, E., Galizia, F. G., Gamberi, M.: Reconfigurable manufacturing system design using a genetic algorithm. In: Proceedings of the International Conference on Sustainable Design and Manufacturing, pp. 130–139. Springer, Singapore (2021)
14. Holland, J.H.: Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence. MIT press (1992)
15. Shukla, A., Pandey, H. M., Mehrotra, D.: Comparative review of selection techniques in genetic algorithm. In: 2015 International Conference on Futuristic Trends on Computational Analysis and Knowledge Management (ABLAZE), pp. 515–519. IEEE (2015)
16. Bhoskar, M.T., Kulkarni, M.O.K., Kulkarni, M.N.K., Patekar, M.S.L., Kakandikar, G.M., Nandedkar, V.M.: Genetic algorithm and its applications to mechanical engineering: a review. Mater. Today Proc. **2**(4–5), 2624–2630 (2015)
17. Min, H.: Genetic algorithm for supply chain modelling: basic concepts and applications. Int. J. Serv. Oper. Manag. **22**(2), 143–164 (2015)
18. Dou, J., Dai, X., Meng, Z.: A GA-based approach for optimizing single-part flow-line configurations of RMS. J. Intell. Manuf. **22**(2), 301–331 (2011)
19. Abbasi, M., Houshmand, M.: Production planning and performance optimization of reconfigurable manufacturing systems using genetic algorithm. Int. J. Adv. Manuf. Technol. **54**(1), 373–392 (2011)
20. Katoch, S., Chauhan, S.S., Kumar, V.: A review on genetic algorithm: past, present, and future. Multimed. Tools Appl. **80**(5), 8091–8126 (2020). https://doi.org/10.1007/s11042-020-10139-6
21. Pandey, H.M., Chaudhary, A., Mehrotra, D.: A comparative review of approaches to prevent premature convergence in GA. Appl. Soft Comput. **24**, 1047–1077 (2014)
22. Hassanat, A., Almohammadi, K., Alkafaween, E., Abunawas, E., Hammouri, A., Prasath, V.B.: Choosing mutation and crossover ratios for genetic algorithms—a review with a new dynamic approach. Information **10**(12), 390 (2019)
23. Lin, W.Y., Lee, W.Y., Hong, T.P.: Adapting crossover and mutation rates in genetic algorithms. J. Inf. Sci. Eng. **19**(5), 889–903 (2003)

# Knowledge Base Materials Sustainable Science Communication on Advanced Materials

Katja Nau[1(✉)], Sara Espinoza[2], Harald F. Krug[3], Clarissa Marquardt[1], Andreas Mattern[4], Nadja Möller[2], Christoph Steinbach[2], and Dana Kühnel[4]

[1] Institute for Automation and Applied Informatics (IAI), Karlsruhe Institute of Technology (KIT), Hermann-Von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
katja.nau@kit.edu

[2] Society for Chemical Engineering and Biotechnology (DECHEMA), Theodor-Heuss-Allee 25, 60486 Frankfurt Am Main, Germany

[3] NanoCASE GmbH, St. Gallerstr. 58, CH-9032 Engelburg, Switzerland

[4] Department Bioanalytical Ecotoxicology (BIOTOX), Helmholtz Centre for Environmental Research (UFZ), Permoserstraße 15, 04318 Leipzig, Germany

**Abstract.** Transparent and reliable communication of the safety of advanced and nanomaterials is an issue that has become increasingly important in recent times. The German initiative DaNa got involved in this topic at an early stage. It is running the Knowledge Base Materials, a web-based information platform on nanomaterials (www.nanoobjects.info) for more than 10 years, which is constantly being expanded. Recently, due to emerging developments in materials science, the focus has been expanded from nanomaterials to the variant-rich group of advanced materials, softening the restriction to particles below the 100 m size limit in one dimension to include larger particles with more complex composition. For the Knowledge Base Materials, this broader scope presents a challenge for science communication. In this paper, the authors describe the selection of materials, the workflow, and the quality control that was performed to provide reliable knowledge about the safety of advanced materials to humans and the environment.

**Keywords:** Science communication · Knowledge base · Advanced materials

## 1 Introduction

Materials, especially advanced materials, are the backbone and source of prosperity of a modern industrial society. These advanced materials will play a decisive role in the future. Advanced materials are designed with a purpose to have novel or enhanced properties and improve performance over conventional materials, products, and processes.

Various material innovations hold great promises to tackle today's societal challenges such as energy generation and storage, building sustainable cities, mobility or even in the global fight against diseases. To keep up with this development, the scope of the existing Knowledge Base Materials was broadened to cover advanced materials with nanomaterials representing a sub-group. Similar to the usage of nanomaterials, innovations containing advanced materials should be as safe as possible, meaning not


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 33–42, 2023.
https://doi.org/10.1007/978-981-19-9205-6_4

causing any harm towards humans and the environment. At the same time, advanced materials should not generally be perceived as a cause for concern.

In any case, a clear definition of advanced materials is difficult and has not yet been established. The term material is far-reaching and stands for the basic building blocks of all physical objects. Novel as well as known materials can be optimized or tailored to fulfil specific functionalities and address different challenges. An attempt to classify advanced materials suggests that the term refers to "materials representing an advance over conventional materials either by controlling their composition and structure or through new modifications". A good basis for defining advanced materials is provided by Javier Peña's report from 2013 [1]. Advanced materials are described as a heterogeneous group that may include nanomaterials, bioactive, anisotropic materials, among others (see Table 1). Each one has different properties and varies in composition, shape, size, interactions, and charges, resulting in a wide range of functionalities and behaviors [1, 2]. They are expected to be essential for human well-being and economic security, with applications in numerous industries including those aimed at addressing affordable and clean energy and resilient infrastructure, future key challenges to cope with the consequences of climate change [3–6].

The development and commercialization of products with advanced materials requires an accurate risk assessment of such products and appropriate risk communication measures. Risk communication and public awareness are key to avoid unjustified negative public perception and a backlash of public concern [7, 8]. This perception is also influenced by existing binding principles (such as the EC precautionary principle [9]), definitions and regulations [8, 10].

In this paper, the authors illustrate how they established the Knowledge Base Materials on advanced and nanomaterials as a web-based application (www.nanoobjects.info) and how they contribute in this way to sustainable information on advanced and nanomaterials for interested stakeholders.

## 2 Methodology

### 2.1 Selection of Advanced Materials

For a novel material to be included in the Knowledge Base Materials (www.nanoobjects.info) two main criteria apply: market relevance and existence of relevant toxicological studies. Guiding questions are i.e. "Is the material already available in a product on the market or will it be available soon?" and "Is there sufficient scientific knowledge published on material safety?". The latter question is the most decisive factor as the DaNa project focusses on processing published research data from the scientific literature for science communication purposes and does not conduct its own laboratory research.

Javier Peña's report provides a good basis for expanding the existing knowledge base to include advanced materials [1]. Table 1 summarizes material categories with examples of possible materials / material classes.

### 2.2 Selection Criteria and Quality Check of Publications

Various factors contribute to a successful and objective communication of scientific findings to a broader community. Ensuring good quality, reliability and comparability

**Table 1.** Main categories of advanced materials and examples for each category. It follows the categorisation as suggested in [1] as well as in [11].

| Material category | Examples |
|---|---|
| Fibres | PECH / PAN based carbon fibres |
| Bio based | DNA origami |
| Advanced textiles and fibres | Self-cleaning fabrics |
| Advanced manufacturing | 3D-printing |
| High performance polymers | Self-healing polymers |
| Light alloys | Titanium-, Magnesium-based |
| Active materials | Micro-encapsulated phase-change materials |
| Gels and foams | Aerogel |
| Layers | Graphene |
| Coatings | Electrically-conductive ink |
| Nanomaterials | Nanowires |
| Advanced composites | Organic light-emitting diode |

of the research studies conducted are impertinent to draw reliable conclusions from the results, whether for scientific or regulatory purposes or for the information of interested stakeholders via the Knowledge Base Materials. Due to the huge amount of nanotoxicology studies published annually, this became even more important [12]. The number of publications for advanced materials has not even been recorded yet.

To address the issue of accuracy and reliability of scientific studies, the implementation of a comprehensible procedure for study quality control is an important step: First, the most critical parameters and factors influencing (toxicological) studies on advanced materials (including nanomaterials) are identified and compiled by different experts. These cover material properties, dispersal of materials for toxicological tests, the toxicity study design itself and additional criteria such as usage of Standard Operating Procedures (SOPs) or other official test guidelines.

As a result, the literature criteria checklist "Methodology for selection of publications" was established. It is a functional and comprehensive tool for evaluating published research studies for reusage, with specific focus on science and risk communication on nanomaterials [13, 14].

At the same time, the tool makes the evaluation process objective, transparent and comprehensible. The fulfilment of mandatory and voluntary criteria allows a differentiated weighing on quality and reliability of study results (Fig. 1). Similar approaches for evaluating study quality differing in purpose and degree of details have also been developed by others, e.g. [16–20].

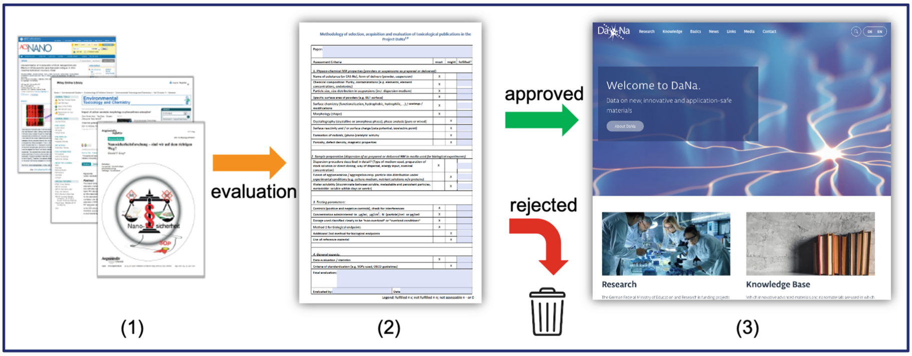



**Fig. 1.** DaNa writing process for article creation: (1) Bibliographic analysis of peer-reviewed scientific papers on selected advanced materials. (2) Evaluation of selected papers with the help of the DaNa literature criteria checklist "Methodology for selection of publications" [15]. (3) Approved papers serve as a source of information on the characteristics, human and environmental toxicology of advanced materials and are cited on www.nanoobjects.info.

# 3 Results

## 3.1 Provision of Quality-Checked Publications

**Adaptions on quality criteria for advanced materials studies**

As mentioned before, the term "advanced materials" includes an even broader class of different materials than the term "nanomaterials". Moreover, little is known today on toxicity-relevant properties of many advanced materials. Within the community, the current focus of the discussion is on how to identify materials of concern for human and environmental health [21–23]. As a consequence, the Knowledge Base Materials team constantly monitors the existing study quality criteria checklist for novel criteria that describe the specificities of advanced materials. As the listed criteria need to be applicable to a broad variety of different materials, the team faces the challenge to formulate as precise as possible but not too limiting for only specific criteria. So far, there are only few indications on relevant criteria that need further consideration. For example, with the expansion of the Knowledge Base Materials from nanomaterials to advanced materials, the size factor of the evaluated material is not limited to the nanoscale anymore. However, size and dimensions (shape) of the investigated particulate or fibrous materials should be clearly stated and characterised accordingly. Since a clear definition of advanced materials does not currently exist and also appears impossible in the near future due to the heterogeneity of materials, expert knowledge is indispensable, since the term is used in different contexts and the published research results must therefore also be evaluated in the respective context.

One example for the need to adjust the existing evaluation criteria for ecotoxicity testing are polymer materials, which are used for example as composite materials in 3D printing [24]. On the basis of quality criteria developed for nanotoxicity studies, it was explored if and which additional criteria need to be considered for this specific group of materials (e.g., additive content), and which criteria are not relevant (e.g., porosity).

### 3.2 Knowledge Base Materials Structured Writing Approach

Following the evaluation of study quality, the content of the quality-assured research data is transferred into generally understandable articles. For better clarity for the readers, all texts follow a fixed structure for which a tiered approach has been adopted: each article starts with a short and relatively simple summarizing paragraph (teaser). The scientific details are then further elaborated as the article continues ending with a reference list of the most important quality assured scientific publications for the respective material (Fig. 2).

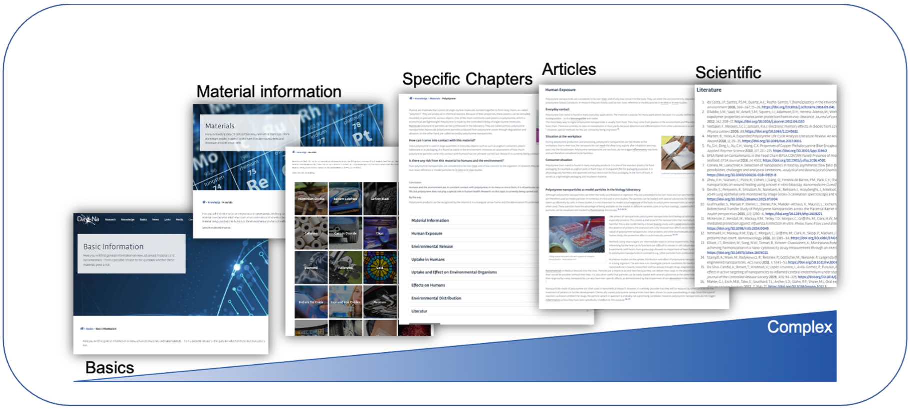



**Fig. 2.** A graduated complexity addresses different educational backgrounds of visitors. The complexity of the information increases from the basic articles to the material overviews and material-related information (1 subchapter) on human toxicology (3 subchapters) and ecotoxicology (3 subchapters) to the cited scientific literature.

For each material, information is provided on the material properties and applications, as well as detailed content on exposure scenarios, behaviour, and hazard assessment for humans and the environment.

The Knowledge Base Materials expert team is working according to a multi-eye principle: the scientific review of the initial article is followed by a second review conducted by a non-scientist, which focuses on the implementation of general comprehensibility. Since technical terms cannot be completely avoided, a separate glossary is provided to further improve general understandability.

If a new material fulfils the previously mentioned criteria to be added into the knowledge base, the content creation process is started. A brief fact sheet summarising the most important information is compiled, allowing the reader to get a quick overview and creating interest in reading further. This is followed by more detailed information on the material itself as well as the relevant toxicological aspects for humans and the environment.

**Material Information - Properties and Usage**

Each material presented is characterized in the "Material Information" section. General information on properties and use as well as occurrence and production are provided. A guideline of questions is applied during article creation to provide a structured guidance for the author as well as a clear orientation for the reader to find information later on in a targeted way. In addition, for regular users a recognition effect is created.

**Toxicological aspects of advanced materials for humans**

The mentioned principles of the predefined writing scheme are also applied to the creation of articles for the topic of human toxicology. Evaluated scientific publications are sorted according to the main topics addressed in the Knowledge Base, namely (I) *Human exposure*, (II) *Uptake in humans* and (III) *Effects in humans*. Again, a specific set of guiding questions structures the article and guides the reader through the provided information. The catalogue of questions for the topic of exposure to humans encompasses questions such as: *Are epidemiological studies available? In which (everyday-relevant) applications do people come into contact with a (nano)material? What is the situation at the workplace? What about the release of materials at the workplace? Is the worker exposed to material at the workplace?*

Since the knowledge base is primarily aimed at citizens without scientific knowledge in toxicology, it is important to consider the situation of the consumer. Thus, relevant questions to be addressed are: *Is it possible for the materials to be released from consumer products? How likely is the exposure and what are the effects?* For this purpose, in vitro and in vivo studies are evaluated. The next stage is the uptake of released materials into the human body. Here, studies on the lung, skin and gastro-intestinal tract are being considered. In the process, the focus is on aspects such as the following: *Which absorption mechanisms are relevant for the different forms of the material (bulk/nano)? Which uptake mechanisms are relevant for the different forms of the material or are there relevant differences for the material in different forms? What happens to the material in the lung (e. g. removal from the body, inflammation or absorption into the body)?*

In addition, the effects of materials on humans after the uptake are also being covered. *How is the distribution and effect in the body? Will the material be taken up in cells and if so, in which way?* The answers to the questions on uptake and behaviour are important to draw final conclusions for the hazard and overall risk assessment of the material related to human toxicology. They ensure to cover topics of specific interests for the general public related to material safety.

**Environmental impact of advanced materials**

Analogous to the previous section, specific guiding questions serve as a blueprint for a uniform structure of this texts. Three individual sections inform on (I) *Environmental release & exposure* of advanced materials, their (II) *Behaviour in the environment*, and (III) *Uptake and effects in environmental organisms*.

Accordingly, the following questions are considered: *Is there a release at all? At which stage of a products life cycle? What and how much material is released into the environment? Into which compartment? How is the material behaving regarding transformation and transport processes?* And finally, *Is the material taken up by environmental organisms, is it affecting the organisms?*

Especially the last question needs attention in order to provide a balanced overview on environmental safety. For advanced materials it is important to consider toxic effects resulting from the specific form (shape, dimensions), the materials composition, or from by-products (e.g., endotoxins, additives), which are contained in the material.

## 4 Lessons Learnt

Scientific conferences, publications and textbooks are the usual channels for scientists to communicate their results. However, websites and social media are becoming more and more important in the present time. However, fake news and false information are also on the rise. Consumers often cannot evaluate scientific information and scientific terms and cannot distinguish them from such false information. As a scientist, however, you also strive to communicate findings to a broad audience. In order to provide validated fact-based information to a broad interested audience via a public website, the consecutive German DaNa projects were initiated with the aim of communicating data and knowledge on the safety of advanced and nanomaterials. These science communication projects were intended to avoid repeating the previous communication failures of other branches of science, such as genetic engineering or nuclear power. Scientific results on the safety of advanced and nanomaterials should be presented in a transparent and structured manner at an early stage of technology and application development. Since 2009, scientists in these initiatives have been working in the area of tension between precise scientific facts on the one hand and simplified presentations on the other. The result is the current web-based Knowledge Base Materials (via www.nanoobjects.info). From the authors perspective, the established quality assurance procedure facilitates the unbiased and transparent assessment of scientific outputs in alignment with community-validated characteristics [15]. In addition, the implementation of mandatory and voluntary criteria gives the evaluators a certain amount of freedom to individually rate and judge certain aspects of the selected studies from an expert's point of view. The template of the literature criteria catalogue is available online in order to make the process of evaluating the literature transparent. The question-guided writing scheme supports a harmonized summary of the compiled scientific information to give answers to the most relevant questions for the target groups.

This general article structure implemented on the website for all listed materials within the knowledge base creates an expert-guided user experience with high recognition value. Complex information derived from scientific publications on the safe handling of advanced and nanomaterials is presented in a structured, comprehensible and comparable way. The increase of content complexity from basic articles to material-specific descriptions of safety-relevant aspects with the corresponding scientific literature caters to the background and needs of the different stakeholder groups such as interested citizens, journalists or scientists.

This information is supplemented by a FAQ collection and a glossary. If the website visitors still have unanswered questions, they can directly interact with the expert team behind the knowledge base via a contact form. Thus, an open discussion on the safety of advanced materials and nanomaterials is facilitated.

## 5 Conclusion

Today, science has an even greater responsibility to provide fact-based answers and to develop solutions to most urgent issues of current times, such as climate change, health research or digitalisation. This responsibility also encompasses the major task of science communication. A dialog with the public must be conducted, current debates must be presented in a factual manner, and the challenges and opportunities of new scientific developments must be highlighted. Both funding agencies and EU wide policy put currently big emphasis on the importance of science communication [25–27]. Science communication needs to be driven by the scientists and has to become a constant part of the science system. Besides the sharing of scientific outputs, the processes and methods used to achieve these results need to be shared with the public to create more transparency, explain the complex and provisional nature of scientific results and thus strengthen trust in the scientific community. To initiate this transformation of science communication becoming an integral part of the science system, e.g., in Germany the initiative "#FactoryWisskomm" was set up in 2021. Within this think tank exchange format, representatives from politics, science communication and science journalisms have formed working groups around the most important topics to create recommendations and strategic next steps for the field of science communication [28]. These cover e.g., science journalism in the digital age, public engagement formats for science communication or quality assessment & quality management in science communication.

As presented in this paper, the concept of the web-based Knowledge Base Materials provides processed fact-based structured results on the safety of advanced and nanomaterials (www.nanoobjects.info). This approach generated by an expert team of different research disciplines (biology, chemistry, material sciences, toxicology) has successfully set up this objective information source with easy online access for different stakeholder groups. This processing of scientific findings is also transferrable to the novel developments in material science and the team is currently working on the generation of new content for the novel classes of advanced materials. As with any scientific field, the process is constantly monitored and adjusted accordingly upon recent updates from the scientific community.

Taken together, the overall science communication activities of the team have strongly contributed to the science and risk communication for nano- and now advanced materials as part of risk assessment, thus promoting a sustainable and responsible use of these materials in future.

**Acknowledgments.** The authors would like to thank the Federal Ministry of Education and Research (BMBF) for funding (DaNa4.0 Information on the safety of new, innovative materials and nanomaterials, FKZ 03XP0282).

## References

1. EU: DAMADEI Design and Advanced Materials As a Driver of European Innovation (2013)
2. Kennedy, A., et al.: A definition and categorization system for advanced materials: the foundation for risk-informed environmental health and safety testing. Risk Anal. **39**(8), 1783–1795 (2019)
3. Goel, P., et al.: Perovskite materials as superior and powerful platforms for energy conversion and storage applications. Nano Energy **80**, 105552 (2021)
4. Lee, G.-H., et al.: Multifunctional materials for implantable and wearable photonic healthcare devices. Nat. Rev. Mater. **5**(2), 149–165 (2020)

5. Fernandez, C.A., et al.: Progress and challenges in self-healing cementitious materials. J. Mater. Sci. **56**(1), 201–230 (2020). https://doi.org/10.1007/s10853-020-05164-7
6. Li, X., et al.: Metal–organic frameworks as a platform for clean energy applications. EnergyChem **2**(2), 100027 (2020)
7. Siegrist, M., Hartmann, C.: Consumer acceptance of novel food technologies. Nat. Food **1**(6), 343–350 (2020)
8. Joubert, I.A., et al.: Public perception and knowledge on nanotechnology: a study based on a citizen science approach. NanoImpact **17**, 100201 (2020)
9. Precautionary principle (April 2022). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:precautionary_principle
10. EC, E.C.: Commission Recommendation of 18 October 2011 on the definition of nanomaterial. (2011/696/EU) (2011). http://data.europa.eu/eli/reco/2011/696/oj
11. Giese, B., et al.: Advanced materials: overview of the field and screening criteria for relevance assessment. In: Dessau-Roßlau, G., ed., p. 106 (2020)
12. Hristozov, D.R., et al.: Risk assessment of engineered nanomaterials: a review of available data and approaches from a regulatory perspective. Nanotoxicology **6**(8), 880–898 (2012)
13. DaNa-Project-Consortium: Literature Criteria Checklist (9 November 2021). https://nanopartikel.info/en/knowledge/literature-criteria-checklist/
14. Nau, K., et al.: The Dana2.0 knowledge base on nanomaterials – communicating current nanosafety research based on evaluated literature data. J. Mater. Educ. **38**(3–4), pp. 93–109 2016
15. DaNa Project-Consortium. Literature criteria checklist - a methodology of selection, acquisition and evaluation of toxicological publications in the Project DaNa. nanopartikel.info 2021 2016 (April 2022). https://nanopartikel.info/en/knowledge/literature-criteria-checklist/
16. Fernández-Cruz, M.L., et al.: Quality evaluation of human and environmental toxicity studies performed with nanomaterials – the GUIDEnano approach. Environ. Sci. Nano **5**(2), 381–397 (2018)
17. Card, J., Magnuson, B.: A method to assess the quality of studies that examine the toxicity of engineered nanomaterials. Int. J. Toxicol. **29**, 402–410 (2010)
18. Faria, M., et al.: Minimum information reporting in bio–nano experimental literature. Nat. Nanotechnol. **13**(9), 777–785 (2018)
19. Schneider, K., et al.: “ToxRTool”, a new tool to assess the reliability of toxicological data. Toxicol Lett **189**(2), 138–144 (2009)
20. Segal, D., et al.: Evaluation of the ToxRTool’s ability to rate the reliability of toxicological data for human health hazard assessments. Regul. Toxicol. Pharmacol. **72**(1), 94–101 (2015)
21. Peijnenburg, W., et al.: Identification of emerging safety and sustainability issues of advanced materials: proposal for a systematic approach. Nanoimpact **23**, 100342 (2021)
22. Giese, B., et al.: Advanced Materials: Overview of the Field and Screening Criteria for Relevance Assessment. Umweltbundesamt (Publisher). 132/2020 (2020)
23. Reihlen, A., et al.: Advanced Materials: Overview of the Field and Screening Criteria for Relevance Assessment. UBA-Texte (2022). **Texte | 09/2022**(Final report): p. FKZ 3719 66 402 0
24. Kokalj, A.J., et al.: Quality of nanoplastics and microplastics ecotoxicity studies: refining quality criteria for nanomaterial studies. J. Hazard. Mater. **415**, 125751 (2021)
25. German Federal Ministry of Education and Research (BMBF): Grundsatzpapier des Bundesministeriums für Bildung und Forschung zur Wissenschaftskommunikation, p. 7. Berlin, Germany (2019)
26. European Research Executive Agency: Towards clearer and more accessible science communication. rea.ec.europa.eu 2022 12.01.2022 (April 2022). https://rea.ec.europa.eu/news/towards-clearer-and-more-accessible-science-communication-2022-01-12-0_en

27. SIS.net Network: Science communication - policy brief. Ref. Ares(2020)1297156 - 02/03/2020, p. 12 (2020)
28. Bundesministerium für Bildung und Forschung (BMBF): HANDLUNGSPERSPEKTIVEN FÜR DIE WISSENSCHAFTSKOMMUNIKATION (2021). https://www.bmbf.de/bmbf/shareddocs/downloads/files/factory_wisskomm_publikation.pdf?__blob=publicationFile&v=2

# Transforming the UK Metal Industries: Challenges and Opportunities

Masoud Ahmadinia[1](✉), Anne Velenturf[2], Rossi Setchi[1], Sam L. Evans[1], Jean McKendree[3], and Jon Bolton[4]

[1] School of Engineering, Cardiff University, Cardiff, UK
ahmadinia.masoud@gmail.com
[2] School of Civil Engineering, University of Leeds, Leeds, UK
[3] Stockholm Environment Institute, York, UK
[4] Materials Processing Institute, Teesside, UK

**Abstract.** The extraction and processing procedures in the metal industries have resulted in a wide range of environmental problems that need to be addressed to achieve net-zero in the UK. The current strategies are heavily biased toward end-of-life phase assessments (such as recycling), possibly neglecting other possible opportunities across entire life cycles, such as advances in product design, manufacturing and in-use phases.

TransFIRe is a proactive, interdisciplinary, inclusive research and practice-driven hub with visions to transform foundation industries. The current work represents the results from TransFIRe's Metal Technical Working Group's workshops and meetings with the industry and academic partners. Discussions covered the drivers and barriers for transformative change in the UK metal industries, actors in control of the drivers and barriers, actions they could take, and any gaps in the expertise they might face. Besides, the presented analysis includes the environmental impacts of UK metal industries and a review of the solutions offered in previous studies and roadmaps to meet Net Zero targets in the UK. PESTLE and SWOT analyses have been provided to help make a systematic and thorough evaluation of UK metal industries and identify and overcome its challenges for transformative change. Our preliminary assessment shows that lack of government support and capital investment, high energy cost, lack of skilled people, limited recycling facilities and strict recycling regulations are some of the main barriers to transforming UK metal industries.

**Keywords:** Circular economy · Sustainable development · Dematerialisation · Resource management

## 1 Introduction

Climate change is a critical worldwide challenge. Metal manufacturing requires large quantities of energy for mining, smelting, refining and recycling, resulting in considerable greenhouse gas (GHG) emissions. The impact of metal extraction, production and processing on climate change and human health doubled between 2000 and 2015


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 43–56, 2023.
https://doi.org/10.1007/978-981-19-9205-6_5

[1]. Metals accounted for 18% of worldwide resource-related climate change and 39% of Particulate Matter (PM) health impacts in 2011 [1]. The worldwide iron-steel production chain has the most significant influence on climate change compared to other metals and accounts for around one-quarter of global industrial energy consumption. Global aluminium production also contributes significantly to climate change due to large production volumes and high energy requirements, whereas toxicity implications are the primary issue for copper and precious metals.

From 1900 to 2015, worldwide steel manufacturing released around 147 billion tonnes (Gt) $CO_2$-eq, accounting for approximately 8% of total GHG emissions [2]. During this period, process efficiency improved by 67%, but it was offset by 40-fold in annual steel production, leading to a 17-fold net increase in GHG emissions [2]. This could demonstrate the insufficiency of process efficiency alone in reducing absolute emissions to some extent [2]. Globally, including in the UK, technical improvements have not been implemented due to competition to reduce costs and a lack of capital. Before 2015, the global steel industry's GHG intensity was stable for 15–20 years [2]. While technological efficiencies have improved over the last few decades, they were overridden by the expansion of low efficient steel production.

After steel, the metal industry with the most significant climate impact worldwide is aluminium, caused by fuel and electricity usage for bauxite ore refining and aluminium smelting. While some improvements have been made, additional energy savings of roughly 10% are still attainable by replacing outdated facilities [3]. For metals where energy is the primary input, renewable sources for electricity would also have a positive impact. For instance, hydro supplies around 75% of the aluminium production in Europe (including the UK), the US and South America [4].

The metal industries play an essential role in the UK economy. The industries are crucial for all other industries, including manufacturing, construction, transportation, power generation, etc. UK metal industries consist of around 11,100 companies and 230,000 employees, directly contributing £10.7 bn to the national GDP; and indirectly 750,000 jobs and £200bn UK GDP [5].

The UK has ambitious visions for upgrading its transportation and energy infrastructure to build a net-zero economy. The UK's demand for resources is expected to skyrocket, draining more than twice its fair global share of known reserves of several crucial raw resources by 2035 (and up to five times by 2050) [6]. The dependency on critical materials also makes UK low-carbon sectors vulnerable. Moreover, the UK might harm the global transition to net-zero emissions by driving the growth of extractive industries and exporting hazardous wastes to low-income, resource-rich countries [7].

In order to minimise the environmental damage caused by UK metal industries, it is essential to move toward a circular economy [5]. The transition of the UK metal industries towards net-zero could be possible by working with the Government, communities and other sectors to create a comprehensive roadmap to maximise energy efficiency and minimise resource use. Besides working on product design for durability and easier disassembly to enable reuse and recycling, UKMC recommended optimising the metal industries' manufacturing processes for waste prevention and greater use of by-products [5]. UK metal industries could embed a sustainability ethos across the industry by promoting best practices, benefiting small companies with lower innovative capacity in particular. Policymakers could support the development of a circular economy by implementing suitable regulations to support responsibly produced UK-based products while promoting durability, reuse, remanufacturing and recycling [5, 8].

TransFIRe is a proactive, interdisciplinary, inclusive research and practice-driven hub with visions for transformative change. TransFIRe envisages optimising flows of resources within and between six foundation industries (FIs, including metals, cement, ceramics, chemicals, glass and paper) and their supply chains by minimising resource use in processes and society and making better use of wastes and by-products. This will improve FIs competitiveness and support UK Net Zero 2050 targets. It will also open opportunities to work with communities in which FIs are located and improve equality, diversity and inclusion in FIs.

Roadmaps to Net Zero for metals align with many of TransFIRe's goals to optimise resources (e.g. use of recycled metals, reduction of metal waste during processing), improve competitiveness and move toward Net Zero (e.g. improve technology). TransFIRe aims to promote maintaining (not necessarily growing) economic prosperity and improve social well-being and environmental quality, in line with global evidence. [9–11].

The FIs have several mutual processes such as heating, cooling, granulation, drying and transportation. Using the *"Gentani principles"*, i.e. minimum resource needed to carry out a process [12], TransFIRe is benchmarking and identifying best practices considering resource efficiencies and environmental impacts across sectors and sharing information horizontally. Moreover, the research investigates the use of waste as raw materials for other sectors. In metals, solutions could include better scrap metal assessment and separation methods, particularly important for aluminium as developing high-performance recycled alloys made from scrap would optimise its use for more applications.

TransFIRe works with communities to develop new business and social initiatives. For example, the warm air and water produced across metal industries can provide low-grade energy capture opportunities. While this method applies to all metal industries, some of the possible options for the steel industry are heat recovery at the coke ovens, rolling mill, annealing line, sinter plant, electric arc and the basic oxygen furnaces. A successful example of waste heat recovery (WHR) is at the Port Talbot Steelworks, where an evaporative cooling system in the Basic Oxygen Steelmaking (BOS) plant was implemented in 2013 to produce steam and electricity. Over the first six years of its implementation, the project led to an expansion of the electrical generation capacity of 12MWe and an indirect reduction in 2.3Mt of $CO_2$ (equivalent to £45M)[13].

TransFIRe is a diverse consortium of twenty investigators from twelve institutions and over 70 companies, trade associations, professional engineering institutes, NGOs and government organisations related to the foundation sector. It aims to include diverse voices in the preparation of plans for the transformation of foundation industries and offer support for the implementation of changes, especially for SMEs (small and medium-sized enterprises) with limited resources for research and innovation. For more information about TransFIRe, please refer to their recently published article [14] or website [15].

This article aims to identify key intervention points for transformative change in the UK metal industries. The study reviews previous roadmaps and publications on transforming UK metal industries and presents the results from a PESTLE SWOT analysis. The analysis consisted of desk-based research, which formed the basis for focused interactions via TransFIRe's Metal Technical Working Group's (TWG) workshops and meetings with our industry and academic partners to identify the drivers and barriers, actors in control of the drivers and barriers, actions they can take, and any gaps in the expertise they might face in delivering transformative change [16]. The authors have contributed to facilitating the Metal TWG workshops and meetings, developing the PESTLE SWOT analysis and drafting a context analysis for UK metal industries.

## 2 Literature Review

There have been many roadmaps for meeting net-zero targets in the UK metal industries [6, 17, 18, 19, 20, 21, 23]. Core pathways for boosting sustainability identified so far include: lowering fossil fuel use, expanding renewable energy use, efficient use of raw materials, improving technology, using scrap, engaging with Government to improve policies, supporting recycling, reuse, improving the design, adopting science-based targets and using carbon removal options such as carbon capture, utilisation and storage (CCUS) to offset residual and historical emissions and provide 'head room' for carbon-intensive sectors. The available roadmaps have a robust agreement on near-term "low regrets" strategies, introduced in the recent UK Government Net Zero Strategy [20]. Low regrets strategies are defined as "current cost-effective actions which will continue to prove beneficial in the future" [24]. While roadmaps have similar nearer-term trends, their overall decarbonisation strategies vary, especially as net-zero goals approach.

Most previous works focused on supply-side solutions to tackle GHG emissions in the metals industries, such as new production technologies, carbon capture and storage, and hydrogen-based production [25]. Meanwhile, due to the uncertainty associated with technical innovation and social constraints, the necessity of demand-side solutions has been highlighted [26, 27], such as material efficiency measures [28]. Some previous works [26, 27] recommended stabilising the world's per capita stock of aluminium and steel below that of the wealthy nations. This could be achieved through lightweight design and more intensive use measures. In other words, to prevent catastrophic climate change effects, countries are suggested to remain within a safe operating area for global metal use. This topic has been widely neglected in previous studies and roadmaps. The common net-zero strategies addressed in previous roadmaps are described below:

### 2.1 Circular Economy

A circular economy seeks to promote resource sufficiency, efficiency and dematerialisation by decoupling progress from unsustainable material use [29]. This will require changes in the practices of producers, consumers and government actors. A circular economy calls for systems thinking as companies are better to focus on whole system optimisation rather than individual gains [30]. It aims to minimise the extraction of natural resources from the environment, maximise waste prevention and optimise the environmental, social, economic and technical values of materials, components and products throughout their consecutive lifecycles [29]. Circular economy strategies can be grouped under measures to narrow the flow of resources (reducing the total size of the resource economy with measures to dematerialise), slow resource flows by extending the period between manufacturing something and the moment it goes to waste (e.g. repair, reuse, remanufacturing) [31], closing resource flows (i.e. recycling) and safely reintegrating resources back into natural biogeochemical processes if they cannot be circulated within our economy [32]. The Ellen MacArthur Foundation [33] presented a circular economy broadly by expanding the 'waste hierarchy', 'circling longer', and enabling cascaded use. This strategy would increase employment, more effectively capture value, reduce supply chain exposure and market risks, and foster stronger customer connections [33].

It would be possible to use less raw materials in the UK by improving freight efficiency, insulating homes, and promoting car-sharing, public transport, and non-motorised travelling. Circular economy approaches such as reusing or repurposing components, such as steel beams, would potentially save 5% and 8% energy in the UK [34]. Material substitutions, lowering the product weight, and using recyclate are other examples that could lead to lower GHG emissions. Moreover, final consumer decisions (whether made by a business, household, or Government) also affect the amount of energy contained in products and reduce energy requirements [35]. Consumption has long been connected with economic growth, and any attempt to limit it is likely to be challenged. However, the concept of 'prosperity without growth' [36] opposing the ongoing economic expansion in wealthy nations has gained considerable support, though less in circular economy studies, and no growth or degrowth is starting to gain momentum. The UK government has acknowledged the potential benefits of enhancing product life in its current waste prevention policy, having previously invested in research into product lifetimes [37]. Potential policies to guarantee minimum product lifetimes were also addressed in the recent European Commission's Circular Economy Package [21]. The recent EU report highlights a need for complete information on the amount of raw materials in products, extractive waste and landfills potentially available for recovery or recycling [38]. The EU is at the forefront of circular economy in its use of secondary raw materials with, for example, more than 50% of metals such as iron, zinc, and platinum recycled, covering over 25% of the EU's consumption. For scarce elements, gallium and indium, needed for renewable energy and high-tech applications, recycling makes only a marginal contribution. In primary production, many battery raw materials such as lithium, nickel, cobalt, graphite and manganese are present in coal-mining areas. Better methods for extracting these from mining waste could create new economic activity in former coal-mining areas while improving the environment. The EU also assumes that reducing resource use and halving waste is feasible by 2030 [38]. The UK did not adopt this target when the circular economy package was transposed into UK policy. In other words, the EU is going for dematerialisation, but the various UK governments are not following suit.

## 2.2 Recycling

In principle, most metals are infinitely recyclable [39], although such recycling rates would likely pose high energy demands and other environmental impacts. Nevertheless, scrap metals for production entail much lower energy consumption and GHG emissions than ore-based primary production [25, 40]. Ideally, primary extraction is recommended to be treated as a high risk, last resort option [6].

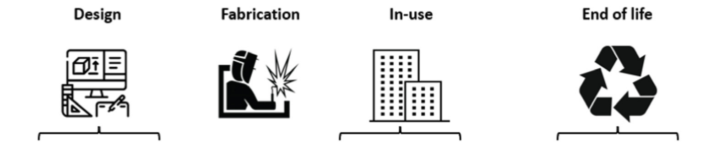
Recycling would positively impact the utilisation of raw material and GHG emissions (especially for aluminium as it is highly recyclable). Like steel, secondary aluminium production reduces environmental impact by eliminating the ore extraction, processing and reduction stages. The climate impact of secondary production could range from 10% to 38% of the primary manufacturing in steel and 3.5% to 20% in aluminium. Energy source differences cause the variations. For example, in secondary steel production, the 10% and 38% climate change compared to primary productions refer to steel produced in renewable energy sourced and coal-fired power plants, respectively. Countries like Norway with renewable energies have a lower impact than India and China, with high reliance on coal-fired power plants. In the case of copper, using scrap would save around 80% of the energy compared to primary production [41].

The emphasis on reuse and recycling is key to the UK's "green growth" strategy and carbon-neutral vision, and the most recent net-zero strategy published by the Government has also discussed the importance of extending the lifetime and lifecycle of a product through sharing, reusing, repairing, redesign and recycling [20]. Secondary production could compensate for the limited physical availability of natural ore to some extent [42]. However, due to dissipative losses, long product lifetimes, and increasing demand, the secondary production would be insufficient to fulfil demand [43]. For instance, even in an ideal world with 90% recycling rates, the forecast demand might deplete current copper deposits by the twenty-first century [44].

## 2.3 Material Efficiency Strategies

While recycling is important, there are vast opportunities to span the entire life cycle, such as light-weighting, substitution, fabrication yield improvements, more intensive use, lifetime extension, reuse, and remanufacturing. A recent work [45] reviewed previous studies on the long-term outlook for future demand, supply and environmental issues of major metals. They reviewed 70 peer-reviewed journal articles published between 1995 to May 2020. They selected articles that analyse the entire metal industry's future condition (after 2025) and its metal flows rather than a limited product. The results illustrated in Fig. 1 show that most studies have focused on the end-of-life phase in material efficiency strategies, of which recycling is the most frequently analysed strategy. In the case of zinc, lead, and nickel, there have been no studies on strategies other than recycling and light-weighting [45]. These metals are critical as some low carbon technologies are dependent on critical raw materials, some of which are rare and only available in unique locations. Some examples are cobalt, lithium and nickel. As scarcity of these materials grows, geopolitics might determine future access.

Another example would be rare earth elements such as neodymium used in magnets. Recent work has suggested that recycling would not be sufficient to meet the rise in demand for metals or reduce environmental impact [46]. Therefore, a comprehensive and comparative assessment of various potential strategies is required to design the environmental policy to directly support governments' and companies' decision-making. Moreover, it is essential to provide science-based targets for major metal flows, stock, circularity, and efficiency. Available tools and digital technologies should be used for more intelligent and efficient production and better traceability and separation processes. Product designs could also be improved to produce a more comprehensive range of products using efficient routes such as using recycled materials.




| | Design: Light-weighting | Design: Substitution | Fabrication: Fabrication yield improvements | In-use: More intensive use | In-use: Lifetime extension | End of life: Reuse and remanufacturing | End of life: Recycling |
|---|---|---|---|---|---|---|---|
| Iron and steel | 7 | 4 | 1 | 5 | 6 | 3 | 30 |
| Aluminium | 3 | 1 | 1 | 0 | 1 | 1 | 14 |
| Copper | 3 | 1 | 0 | 0 | 1 | 0 | 21 |
| Zinc | 3 | 0 | 0 | 0 | 0 | 0 | 9 |
| Lead | 2 | 0 | 0 | 0 | 0 | 0 | 6 |
| Nickel | 2 | 0 | 0 | 0 | 0 | 0 | 8 |

**Fig. 1.** The number of studies on different material efficiency strategies [45].

## 2.4 Dematerialisation

Dematerialisation is defined as reducing raw materials and metals used per capita [29]. Countries can help prevent climate change by remaining within a safe operating area for global metal use. The demands for metals in 2050 have been predicted to grow compared to 2010 as follows [45]: 215% (aluminium), 140% (copper and nickel), 86% (iron), 81% (zinc), and 46% (lead). Besides, the current mining and processing scenarios are not consistent with the Earth's limited resources, and the increase in production is not environmentally sustainable. The depletion year (the year where cumulative production exceeds reserves) for primary metal resources is predicted as 2042 to 2045 for iron, 2030 to 2038 for copper, around 2025 for zinc, 2020 to 2025 for lead, and 2030 to 2040 for nickel [47]. Bauxite is anticipated to be depleted around the middle of the twenty-first century [45]. Besides, the peak year for primary production of major metals is estimated to be 2041 to 91 (iron), 2084 to 2130 (Aluminium), 2030 to 2072 (copper), 2025 to 2061 (zinc), 2018 to 2128 (lead), and 2030 to 2033 (nickel) [45].

The IEA forecast that the 1.5 °C greenhouse gas budget from 2010 to 2050 is around 106 Gt $CO_2$-eq, 37% of which had been exhausted already by 2019. A recent study [2] showed that the 1.5 °C climate target [48] is achievable either through radical reduction of emission intensity with an average of 0.85 t $CO_2$-eq/t steel per decade or a 39%

reduction in steel demand. In other words, to meet climate targets, either the GHG intensity should be decreased immediately, requiring rapid innovation and implementation of low-carbon technologies, or the demand must be reduced significantly. Integrating supply and demand-side measures is essential, as both sides would require less radical changes.

Another study [49] defined five different shared socio-economic pathways (SSP) based on low, medium or high economic and population growth rates (based on climate goal analysis). Their results indicated that metal production's GHG emission reduction target would not be achieved under any possible socio-economic scenarios. It would be impossible to meet climate goals with the predicted increase in future metal demand. In other words, the study suggests that we need to do what is best for the environment, not the economy.

### 2.5 Improving Process Efficiency

Another effective strategy to reduce GHG emissions is to increase operational efficiency through enhanced process control, predictive maintenance strategies and implementation of the best available technologies. For instance, in the case of steel, the blast furnace-basic oxygen furnace (BF-BOF) process relies on pig iron production, limiting it to only around 30% scrap steel. By contrast, the electric arc furnace (EAF) process can use almost 100% scrap steel to produce crude steel. Consequently, the steel produced using BF-BOF creates more than ten times the carbon dioxide emissions of the EAF process (if the manufacture of the original iron is included, then remelting in an EAF is worse) [6]. Currently, UK steelmakers can use up to 6.1 Mt of scrap steel in manufacturing plants. Technologies such as monitoring EAF furnaces with optical emission spectrometry can significantly improve energy and process efficiency [6].

By-products from metal production could provide valuable inputs for other processes or products. Waste heat is an obvious by-product used for heating or steam in the production sites or community heating. Other examples include slag and dust from steel production used to create asphalt, and aluminium drosses and slags, which contain various metals impurities and salts and are reduced to pure salts, which are then used in melting furnaces, potash (used as fertiliser), and aluminium returned for recycling. For instance, the steel produced by Celsa in Cardiff is made from scrap metal using the EAF process, and 93% of process waste is recovered or reused, while the dust from the EAF is used in products like white plastics [50]. SteelPhalt Cardiff uses the slag by-product (on-site at the steel plant) to create asphalt products that contain 95% recycled material with a 40% lower carbon footprint than conventional asphalts [51].

## 3 UK Metal Industries PESTLE Analysis

In order to promote resource recovery efficiency as part of the transition toward a circular economy, it is essential to understand how such a change could be achieved. Circular economy transitions involve diverse stakeholders, and it is therefore essential that relevant stakeholders are involved from the start [29]. Therefore TransFIRe held a Metal

TWG Workshop in January 2022. The workshop facilitated a two-way conversation, and the participants included representatives from academia and industry.

Participation processes can help to explore different opinions from multiple stakeholders about a particular challenge and develop a shared understanding. This can become a basis to frame radical, transformative changes such as those required to transition towards a sustainable circular economy. The academic community can adapt these techniques to contribute to the development of transformative change through participatory action research (PAR). PAR approaches aim to bring societal change and contribute to scientific progress through a cycle of activities including [52, 53]: forming a stakeholder group (1), analysing problems and identifying solutions (2), sharing and reflecting upon solutions and implementing change (3), evaluating the PAR process (4), close or starting a new PAR process [52, 53].

Participatory Situational Analysis (PSA) is a variation on PAR, bringing together academic, government and industry partners with a view to articulate an action-oriented agenda for the development of research programmes and/or the uptake of research outcomes [54]. The PSA approach was followed (Fig. 2) to identify the key actions and gaps in expertise to enable transformative change that specific actors could take to either remove barriers or make the most of the drivers for transformative change [16]. Drivers and barriers were identified prior to the workshop via analyses of relevant roadmaps and a PESTLE SWOT analysis presented at the workshop as the starting point for discussion.

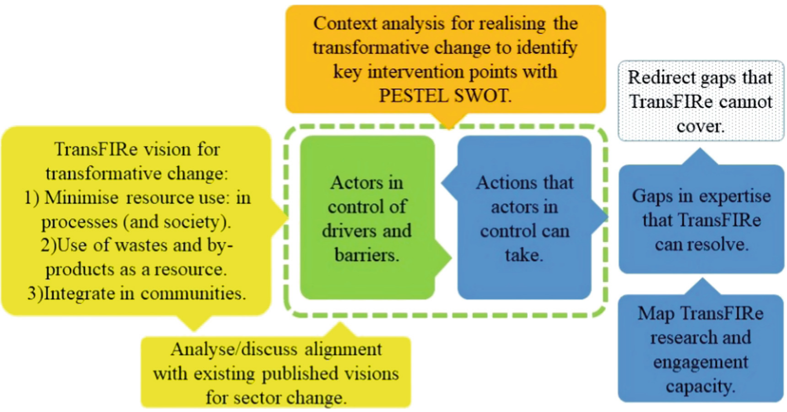



**Fig. 2.** A schematic of our adapted participatory situational analysis strategy.

The PESTLE analysis provided in Table 1 helps to better understand the strategic orientation by evaluating the impact of the external environment on the industry.

Although we know each industry's used resources and generated wastes, it is important to conduct a comprehensive analysis with a circular economy mindset. Another challenge would be the classification of wastes as hazardous, which could be prevented by allowing specific pre-treatments to make the material safe(r) to recycle. For instance, contaminants such as chlorides on the metal surface should be removed from the wastes before classification [55]. The main actors in control of actions that can lead to transformative change in the UK metal industries are as follows:

**Table 1.** The PESTLE analysis for the UK metal industries

| | Driver | Barrier |
|---|---|---|
| Political | Net-zero commitment by 2050 | Lack of: long-term stability in Government policy, Government funds, BEIS engagement with sectors, long-term decisions, regional Government investments, comprehensive definition of waste |
| Economic | Growing demand to reduce $CO_2$/increasing number of Infrastructure Projects/to achieve net-zero, metal is needed in infrastructure/increasing metal demand | High energy costs/high cost and low availability of raw materials/pressure to reduce $CO_2$/Non-UK owners are not willing to invest/high cost of low carbon metals/lack of funds for net-zero-compatible technologies |
| Social | | Skill gap/the sector is not attractive to job seekers |
| Technological | Intelligent manufacturing would provide more control and lower emissions and lead to a higher quality production | Limited infrastructure for scrap sorting/poor relationship between scrap merchants and sector/scrap merchants not involved in research/lack of funds to bring technologies into full-scale deployment/lack of certification for green products/limited circular business model innovation and servitisation |
| Environmental | Restricting recycling policy | Greenwashing/no clarity or agreement on who should be tracking recycled contents/restricting recycling policy/lack of local recycling facilities |

- Political (and Legal): Department for Business, Energy and Industrial Strategy (BEIS), Treasury
- Economic: Investors, oversea owners, Government;
- Social: Schools, Government, NGOs, industry;
- Technological: Industry, R&D;
- Environmental: local Councils, BEIS, industry, consumers, media.

## 4 UK Metal Industries SWOT Analysis

SWOT analysis (Table 2) helps maximise the strengths and opportunities of a system and minimise weaknesses and threats. According to the results, the UK metal industries are suggested to develop strong economic cases on decarbonisation using the existing clusters such as South Wales Industrial Cluster and East Coast Cluster. For this purpose, the industry can engage more with BEIS (construction and materials units) and try to make longer-term decisions. The Government is also recommended to promote repair, reuse and recycling in the UK.

**Table 2.** The SWOT analysis for the UK metal industries

| Strengths |
|---|
| High rate of employment/R&D departments/comprehensive energy management system/willingness to make climate change a priority |
| Weaknesses |
| Employment is uneven across the UK/net-zero technology is uncertain/not efficiently using the available scraps |
| Opportunities |
| Metal is vital for other sectors/Government is committed to supporting the sector |
| Threats |
| High energy costs/challenges in competing for and securing public contracts/vulnerable to global trade |

## 5 Conclusions

Production-based carbon-cutting approaches are not enough to reach net-zero, and it is essential to develop more effective solutions for reducing future GHG emissions from the metal industries. Due to the rapid increase of metal flows (production and consumption) and limited scrap supply, primary routes have dominated production, leading to increased GHG intensity. It would be impossible to meet climate targets with the predicted increase in demand, and demand-side reductions are also needed.

According to the available road maps for the UK metal industries and the inputs from our industry and academic partners in the TransFIRe's metal TWG workshops, the main barriers to transforming the UK metal industries are lack of Government intervention and support, lack of capital investment and business models, lack of skills and people, limited recycling infrastructure (thus high transportation cost), regulatory barriers (e.g. REACH and ROHS ban or restrict the use of metals) and greenwashing. The following actions are recommended to make the UK metal industries more sustainable:

- BEIS needs to develop a more comprehensive strategy to decarbonise metal, including demand-side measures, dematerialisation and durability.
- More robust targets are needed to enforce the use of UK metals in Government-funded projects.
- Long-term finance such as pension funds is needed to support local economies and manufacturing. Investors and Government should invest in local communities and low carbon projects. Starting with the regions, the government is recommended to develop a robust economic case.

- In collaboration with the industry, schools and the Government should promote educational programmes accredited by the industry for primary schools, secondary schools and lifelong learning. Moreover, re-educating the education system is needed based on the jobs offered in the FIs to tackle the skill gap in the industry.
- The industry should make the UK metal industries more attractive for job seekers, for example with better equality, diversity and inclusion performance and green jobs.
- There is a lack of funds to bring technologies into full-scale deployment. Besides, there is a poor relationship between scrap merchants and the metal industry. An appropriate, coherent and supportive policy and regulatory framework are needed for recycling. Government and industry should foster transparency and promote design for recyclability and recycling supply chains within the country for which more local recycling facilities are needed.
- A better understanding of the technical issues in the sector is needed. For instance, it is important to consider and discuss the effects of lubricants, coating and coolants on the recycling process.

**Acknowledgements.** The Transforming the Foundation Industries Research and Innovation hub (TransFIRe (EP/V054627/1)) is funded by UKRI (https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/V054627/1).

## References

1. Oberle, B., et al.: Global resources outlook. In: 2019: International Resource Panel, United Nations Envio (2019)
2. Wang, P., et al.: Efficiency stagnation in global steel production urges joint supply-and demand-side mitigation efforts. Nat. Commun. **12**(1), 1–11 (2021)
3. International Aluminium Institute, Global Aluminium Cycle 2016 (2018)
4. IEA, Aluminium (2021)
5. UKMC. A Foundation Indsustry (2022) https://www.ukmetalscouncil.org/. Accessed 7 Apr 2022
6. GFG Alliance, Making GreenSteel Today's Low-Carbon Reality (2021)
7. Evans, S., Plumpton, H., Peake, L.: Critical point - Securing the raw materials needed for the UK's green transition London (2021)
8. Velenturf, A.P.: A framework and baseline for the integration of a sustainable circular economy in offshore wind. Energies **14**(17), 5540 (2021)
9. Wiedmann, T.O., et al.: The material footprint of nations. Proc. Natl. Acad. Sci. **112**(20), 6271–6276 (2015)
10. Raworth, K., Doughnut Economics: Seven Ways to Think like a 21st-Century Economist. Chelsea Green Publishing (2017)
11. Parrique, T., et al.: Decoupling Debunked: Evidence and Arguments Against Green Growth as a Sole Strategy for Sustainability. Brussels (2019)
12. Blomsma, F., et al.: Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. J. Clean. Prod. **241**, 118271 (2019)
13. Giles, A., et al.: A waste heat recovery strategy and its deployment: an integrated steelworks case study. In: Proceedings of the Institution of Civil Engineers-Waste and Resource Management. Thomas Telford Ltd. (2021)

14. Jolly, M., et al.: The UK transforming the foundation industries research and innovation hub (TransFIRe). In: REWAS 2022: Developing Tomorrow's Technical Cycles (Volume I), pp. 341–353. Springer (2022)
15. TransFIRe. TransFIRe (2022). https://transfire-hub.org/. Accessed Feb 2022
16. Velenturf, A., et al.: Participatory Situational Analysis: How can policy and regulation support resource recovery? Synthesis workshop report (2018)
17. Metals Forum, Vision 2030, The UK Metals Industry's New Strategic Approach (2015)
18. DECC and BIS, Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 (2015)
19. BEIS, Industrial Decarbonisation Strategy. London, UK (2021)
20. BEIS, Net Zero Strategy: Build Back Greener (2021)
21. Commission, E.: Circular Economy Action Plan for a Cleaner and More Competitive Europe. Belgium, Brussels (2020)
22. The Aluminium Federation, Uk Aluminium Sustainability Roadmap to 2050. (2021)
23. International Energy Agency: Iron and Steel Technology Roadmap, IEA. Towards more sustainable steelmaking, Paris (2020)
24. BEIS, Heat and Buildings Strategy (2021)
25. Morfeldt, J., Nijs, W., Silveira, S.: The impact of climate targets on future steel production–an analysis based on a global energy system model. J. Clean. Prod. **103**, 469–482 (2015)
26. Liu, G., Bangs, C.E., Müller, D.B.: Stock dynamics and emission pathways of the global aluminium cycle. Nat. Clim. Chang. **3**(4), 338–342 (2013)
27. Milford, R.L., et al.: The roles of energy and material efficiency in meeting steel industry CO2 targets. Environ. Sci. Technol. **47**(7), 3455–3462 (2013)
28. von Stechow, C., et al.: 2° C and SDGs: united they stand, divided they fall? Environ. Res. Lett. **11**(3), 034022 (2016)
29. Velenturf, A.P., Purnell, P.: Principles for a sustainable circular economy. Sustain. Product. Consum. **27**, 1437–1457 (2021)
30. Cooper, S.J., Hammond, G.P.: 'Decarbonising' UK industry: towards a cleaner economy. Proc. Inst. Civil Eng.-Energy **171**(4), 147–157 (2018)
31. Bocken, N.M., et al.: Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. **33**(5), 308–320 (2016)
32. Velenturf, A.P., et al.: Circular economy and the matter of integrated resources. Sci. Total Environ. **689**, 963–969 (2019)
33. MacArthur, E.: Towards the circular economy, economic and business rationale for an accelerated transition. Ellen MacArthur Found. Cowes, UK, 21–34 (2013)
34. Cooper, S.J., et al.: Thermodynamic insights and assessment of the circular economy. J. Clean. Prod. **162**, 1356–1367 (2017)
35. Griffin, P.W., Hammond, G.P.: The prospects for 'green steel' making in a net-zero economy: a UK perspective. Global Trans. **3**, 72–86 (2021)
36. Jackson, T.: Prosperity without growth? the transition to a sustainable economy (2009)
37. Environmental Resources Management, Longer Product Lifetimes, Summary Report, Department for Environment, Food and Rural Affairs. London, UK (2011)
38. European Commission, Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. Brussels (2020)
39. Reck, B.K., Graedel, T.E.: Challenges in metal recycling. Science **337**(6095), 690–695 (2012)
40. Pauliuk, S., et al.: The steel scrap age. Environ. Sci. Technol. **47**(7), 3448–3454 (2013)
41. Alliance, C.: Copper's Contribution to a low-Carbon Future - A plan to Decarbonise Europe by 25 Percent. Belgium, Brussels (2014)
42. Van der Voet, E., et al.: Environmental implications of future demand scenarios for metals: methodology and application to the case of seven major metals. J. Ind. Ecol. **23**(1), 141–155 (2019)

43. Elshkaki, A., et al.: Resource demand scenarios for the major metals. Environ. Sci. Technol. **52**(5), 2491–2497 (2018)
44. Schipper, B.W., et al.: Estimating global copper demand until 2100 with regression and stock dynamics. Resour. Conserv. Recycl. **132**, 28–36 (2018)
45. Watari, T., Nansai, K., Nakajima, K.: Major metals demand, supply, and environmental impacts to 2100: a critical review. Resour. Conserv. Recycl. **164**, 105107 (2021)
46. Ciacci, L., et al.: Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28. Glob. Environ. Chang. **63**, 102093 (2020)
47. Elshkaki, A., Reck, B.K., Graedel, T.: Anthropogenic nickel supply, demand, and associated energy and water use. Resour. Conserv. Recycl. **125**, 300–307 (2017)
48. IPCC, Global warming of 1.5 °C: an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change (2018)
49. Yokoi, R., Watari, T., Motoshita, M.: Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals. Energy Environ. Sci. (2022)
50. CELSA, There's more to CELSA than steel, Environmental Statement 2020. Cardiff, UK (2020)
51. Steelphalt (2022). https://www.steelphalt.com/environment.
52. Bacon, C., Mendez, E., Brown, M.: Participatory action research and support for community development and conservation: examples from shade coffee landscapes in Nicaragua and El Salvador (2005)
53. Defoer, T., et al.: Participatory action research and quantitative analysis for nutrient management in southern Mali: a fruitful marriage? Agr. Ecosyst. Environ. **71**(1–3), 215–228 (1998)
54. Velenturf A, et al.: Participatory situational analysis: how can policy and regulation support resource recovery? in synthesis workshop report (2018)
55. Johnson, W.C.: Chloride removal from ferrous substrates. In: CORROSION 98. OnePetro (1998)

# Compressive Behaviour of a Square Origami Surface-Based Lattice Structure Fabricated by Selective Laser Melting

Jian Gao[1], Quanquan Han[1(✉)], Shwe Soe[2(✉)], Zhongyi Liu[1], Jiafeng Feng[3], Zhenhua Zhang[1], and Liqiao Wang[1]

[1] Key Laboratory of High Efficiency and Clean Mechanical Manufacture of Ministry of Education, School of Mechanical Engineering, Shandong University, Jinan 250061, China
hanquanquan@sdu.edu.cn

[2] Department of Engineering, Design and Mathematics, University of the West of England, Bristol BS16 1QY, UK
shwe.soe@uwe.ac.uk

[3] School of Automotive Engineering, Weifang Vocational College, Weifang 262737, China

**Abstract.** Selective laser melting (SLM) is a metal additive manufacturing process that shows significant advantages in manufacturing lattice structures. In this paper, a novel surface-based square origami structure made of a nickel-based superalloy was fabricated using SLM. Three different wall thicknesses (50, 75 and 100 μm) were used to examine the manufacturability and corresponding compressive behaviour of the manufactured lattice components. Finite element analysis (FEA) was conducted to determine the uniaxial compression and then verified by quasi-static compression testing. The results showed that the components with thinner walls more easily folded and buckled than those with thicker walls, indicating that higher densification strains and energy absorption values may be achieved with thinner walls, although the thicker walls were stronger and could withstand larger loads. This research offers insights into the design and manufacture of advanced lattice structures by providing an improved understanding of the compressive behaviour of surface-based square origami structures.

**Keywords:** Additive manufacturing · Cellular · Simulation · Strength

## 1 Introduction

The lattice structure is a porous formation composed of unit cells arranged periodically in a three-dimensional space. These porous structures offer many advantages, including lightness and high specific strength/stiffness. Because lattice structures are mostly hollow and complex-shaped, fabricating such structures by traditional processing methods is very challenging. The selective laser melting (SLM) process is an additive manufacturing (AM) technology in which a high-powered laser is used to selectively melt powder from bottom to top according to a computer-aided design (CAD) model. The process is quite accurate for forming and, in theory, can be used to manufacture metallic parts with any


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 57–66, 2023.
https://doi.org/10.1007/978-981-19-9205-6_6

complex shapes [1]. Compared to other metal AM processes such as electron beam melting and direct metal deposition, SLM offers improved forming accuracy and thus is more suitable for processing lattice structures [2].

Because of its good compression, shock-absorption and energy-absorption performance, the honeycomb structure is widely used in the aerospace sector and further afield [3]. Due to its peculiarity of lightweight, aluminum alloy and titanium alloy have been studied extensively and made into a range of honeycomb structures [4]. However, there are scant studies on the manufacturability and mechanical performance of different lattice configurations in nickel-based super alloy possessing excellent oxidation and corrosion resistance [5]. Since light weighting and energy-absorption performance are highly associated to the design and fabrication of lattices with the least material possible, the research question lies on the overall quality (accuracy, surface roughness, and mechanical properties) of minimum wall thicknesses (i.e. $< 1$ mm) that can be successfully manufactured in SLM process.

In the present research, a surface-based square origami structure was manufactured via SLM using nickel-based superalloy material, in order to test the possibility of fabricating very thin walls ($<$ 1mm) and the corresponding compressive behavior. The structure had to be lightweight and strong and show good compression for potential use in the aerospace field, in additional to displaying good shock- and energy-absorption values. To capture the mechanical response under load, quasi-static compression tests were conducted on square origami structures with different wall thicknesses and its buckling and collapse behavior were recorded using a high-resolution camera. Finite element analysis (FEA) was employed to inform the validity of computational and experimental compression responses of square origami structures with different wall thicknesses.

## 2 Materials and Methods

### 2.1 Design of the Square Origami Structure

The lattice structure used in this study is composed of unit cells arranged along an X shape. The unit cell (see Fig. 1a), composed of trapezoidal thin walls (upper bottom: 8 mm; lower bottom: 12 mm), has a rectangular hollow structure (length: 12 mm; width: 8 mm). Three different wall thicknesses of 50 μm, 75 μm and 100 μm were designed to have the relative densities of 0.09, 0.13 and 0.18, respectively. In the build direction, the origami structure consists of three rows of unit cells, each 10 mm high, with a total height of 30 mm.

The isometric view of the sample (see Fig. 1b) shows the origami structure is a cube. Note that the trapezoidal thin-walled structure is symmetrical, and the area where the thin outermost adjacent trapezoidal walls are in contact with the hypotenuse is a band with a spacing of 1 mm. The reason of designing the band shape is to remove the shape edges of the origami structure, where the stress concentration normally occurs during the compression process [6]. In other word, the band shape is designed to achieve a good connectivity between lattices, such that the square origami structure can absorb more energy.

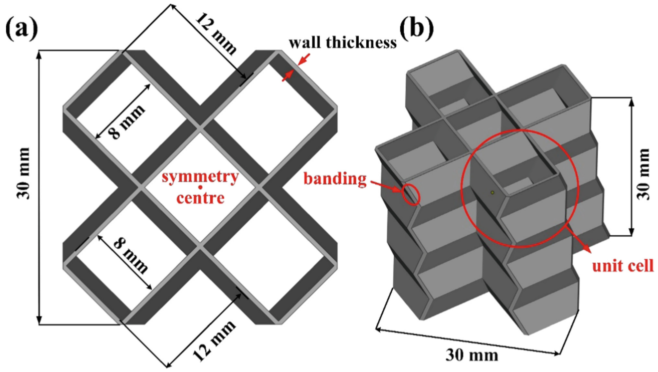



**Fig. 1.** CAD model of a square origami structure: (a) top view; (b) isometric view.

## 2.2 Numerical Modeling Setup

FEA was conducted to understand the stress-strain distribution of the square origami structures during the quasi-static compression process. For FEA, the three above-mentioned CAD geometries with different wall thicknesses were imported into Abaqus as STEP files and compression models. The material used in this experiment is a nickel-based superalloy. Before this compression testing, tensile samples of the nickel-based superalloy were fabricated using SLM. The tensile testing was conducted at room temperature of 25 °C. According to the tensile test data, the elasto-plastic material model was calibrated using Abaqus's calibration tool; the Young's modulus and Poisson's ratio were set to 150.81 GPa, and 0.33. Isotropic plastic hardening model was established with sufficient data points in a tabulated format. Tensile testing was first simulated during the Abaqus FEA to ensure the accuracy of the simulation parameter settings of the compression experiment.

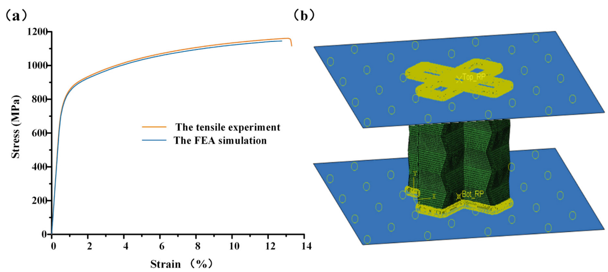



**Fig. 2.** (a) Stress-strain curve of tensile experiment and FEA simulation; (b) simulation model for the FEA compression experiment.

As shown in Fig. 2a, the simulated stress-strain curve was very close to that of the tensile experiment, so the parameters set by the Abaqus FEA provided reasonable fidelity. In the lattice modelling set up, rigid plates are added as boundary conditions to the top and bottom of the model, and each model, finely meshed with C3D8R linear hexahedral elements, was constrained between the analytical rigid surfaces, as shown in Fig. 2b. The general contact condition was imposed for self-interaction. To sustain computational efficiency and robustness Abaqus dynamic explicit solver was employed. During compression the reference point fixed at the centre of the top surface was allowed to move axially when the bottom surface was fully fixed. The reaction force and displacement values, extracted through the described reference point, were translated into compressive stress and strain data. The damaged model with a fracture strain limit, which was mapped to the experimental data, enabled capturing the potential material fracture at the highly stressed regions.

## 2.3 Selective Laser Melting Progress

The material used in this study – a strong, nickel-based superalloy, with good mechanical properties and high-temperature oxidation resistance. The elemental composition of nickel-based superalloys was (wt.%) 22.37Cr-14.05W-2Mo-0.51Si-0.49Mn-0.37Al-0.3Fe-0.11C-Bal. The samples were manufactured using an Mlab cusing 200R SLM (Concept Laser GmbH, Germany), equipped with a 200 W continuous wave fiber laser (Table 1).

**Table 1.** Process parameters for manufacturing origami structure via SLM

| Laser power | Scanning speed | Layer thickness | Hatch spacing |
|---|---|---|---|
| 200 W | 800 mm/s | 40 $\mu$m | 110 $\mu$m |

Three kinds of square origami structures with different wall thicknesses (50, 75 and 100 $\mu$m) were fabricated to study the effect of wall thickness on the compression performance of the square origami structure (Fig. 3).

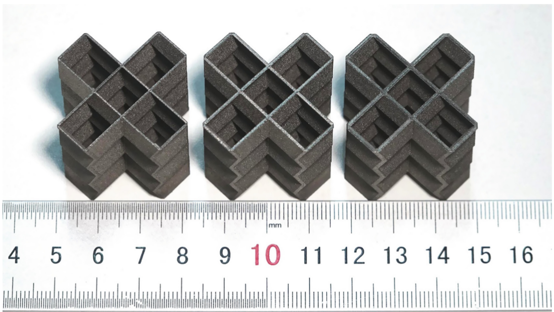



**Fig. 3.** Manufactured square origami structures (50, 75 and 100 $\mu$m).

### 2.4 Quasi-static Compression Testing

Quasi-static compression testing was performed using a universal testing machine (Z250) produced by ZwickRoell, Germany. The compression samples were divided into three groups according to the wall thickness (50, 75 and 100 μm), and each group had three samples to ensure the stability of quasi-static compression test and the reliability of compression test data. The compression rate was set to 2 mm/min for all compression tests. The compression process was recorded by a high-resolution camera to record compression moments to better analyse the failure-deformation behaviour of the square origami structures.

## 3 Results and Discussion

### 3.1 Finite Element Analysis

Figure 4 shows stress-distribution clouds of the three kinds of square origami structures with different wall thicknesses during quasi-static compression via FEA. In the process of compression simulation, the stress concentration occurred in the middle folding area for the origami structure with a wall thickness of 50 μm, which also led to lower compressive strength and stiffness values. The origami structures with thicker walls experienced more uniform stress distribution across all folding regions during compression testing. The corresponding compressive strain values (%) for the displacement at (1, 2, 3.8 and 5 mm) can be interpreted as (3.3, 6.6, 12.7 and 16.6) respectively.

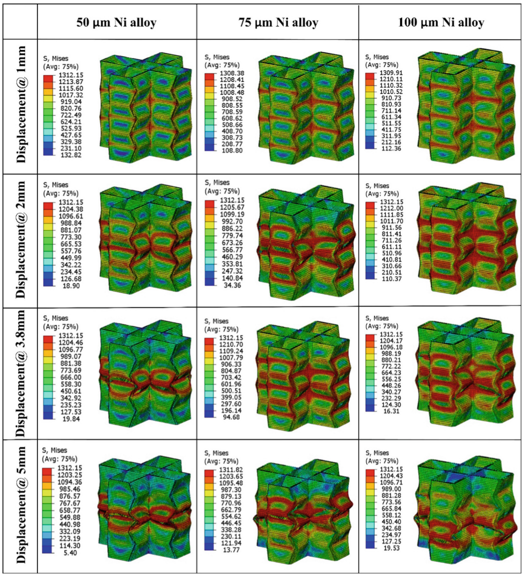



**Fig. 4.** Stress-distribution clouds for FEA compression simulation of three kinds of origami structures with different wall thicknesses.

Figure 5 shows corresponding strain-distribution clouds of the three kinds of square origami structures. In the process of compression simulation, with increased compression displacement, the strain was also found to be evenly distributed in the folding area, which implied that the square origami structure has a good effect of shock- and energy-absorption. The stress-strain distribution simulation results in Figs. 4 and 5 reveal that the square origami structure with different wall thickness shows progressive damage during the compression process. Compared to the compressive direction, the stress and strain are mainly concentrated in the folding area of the square origami structure.

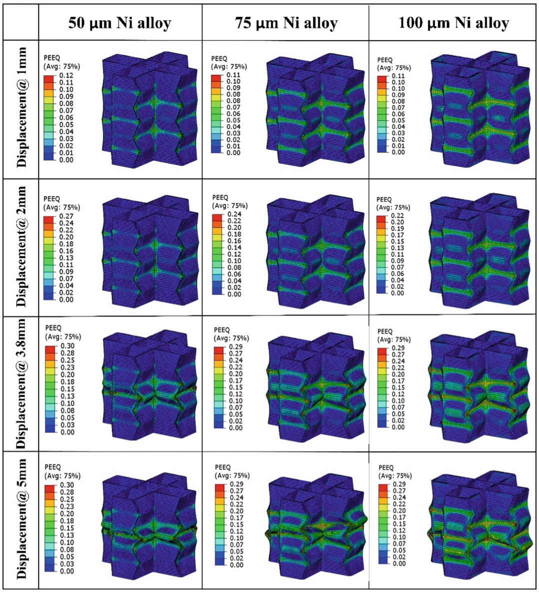



**Fig. 5.** Strain-distribution clouds for FEA compression simulation of three kinds of origami structures with different wall thicknesses.

Figure 6 shows the stress histogram of the square origami structure with different compression displacements. Notably, when the compression displacement reached 3.8 mm, the stress on the origami structure with different wall thicknesses values significantly reduced. It may be concluded that during the stage of compression displacement between 2 and 3.8 mm, the square origami structure changed from the plateau stress stage to the failure stage, and the square origami structure may form cracks initiation and expansion during this stage. As the compression displacement further increased to 5 mm, the microscopic cracks further expanded and eventually caused the failure of the square origami structure.

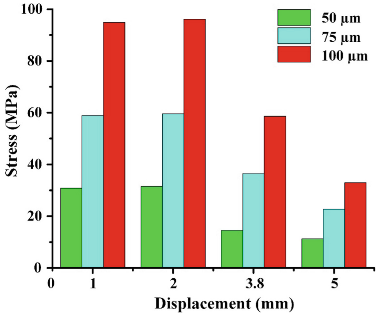



**Fig. 6.** FEA simulated stress diagram under different compression displacements of three kinds of origami structures with different wall thickness values.

## 3.2 Experimental Results

### 3.2.1 Quasi-static Compression Testing Results***

Figure 7 shows the quasi-static compressive stress-strain curves from experiment and Abaqus FEA of three kinds of square origami structures with different wall thicknesses. The compression curves of the three structures were found to show similar trends, which could be divided into three stages:

In the linear growth stage (0–1.5%), the stress-strain curve was approximately a straight line, and the relationship between stress and strain showed a linear relationship, which reflects the strength performance of nickel-based superalloy materials.

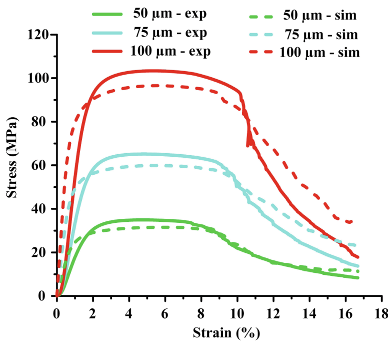



**Fig. 7.** Stress-strain curve diagram of experimentation and FEA for three kinds of square origami structures with different wall thicknesses.

In the second stage (1.5–10%), the stress-strain curve tended to be stable, with a plateau period. In this stage, with increased stress, the square origami structure lost its stability, and folding took place. The amount of deformation along the compression direction continued to increase, and the strain gradually increased. During the compression testing, the energy absorption per unit volume of the square origami structure could be calculated by the following equation [6]:

$$W_v = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \tag{1}$$

where $W_v$ represents the absorbed energy per unit volume, ε is the strain, and $\sigma(\varepsilon)$ represents the corresponding stress.

In the plateau stage, the strain limits of the square origami structures with different wall thicknesses (50 µm, 75 µm and 100 µm) were 7%, 9% and 10%, respectively. The results showed that the origami structures with thinner walls were easier to fold and buckle, indicating that higher densification strains and energy absorption values may be achieved with thinner walls, although the thicker walls were stronger and could withstand larger loads. Consequently, the results offered insights into the design and manufacture of advanced lattice structures by providing an improved understanding of the compressive behaviour of surface-based square origami structures. Note that the maximum strain value of the square origami structure was only 10%, while the maximum strain value of other nickel-based superalloys in the literature could reach 30% [7, 8], which indicated that the nickel-based superalloy used in this study was quite brittle.

Notably, the stress-strain curves obtained by compression experimentation and FEA were generally consistent, but the compressive stress values obtained by experimentation were slightly higher than the values obtained by simulation. From the perspective of FEA, the convergence of the mesh would lead to the simulation data higher than the experimental data. However, this study evaluated both shell and FEA modeling strategies whilst conducting a mesh convergence study to ensure that the extracted data was robust and reliable to be presented. From the perspective of plastic theory, the tensile stress-strain curve and compressive stress-strain curve of a material should be consistent [9]. As previous studies have revealed, however, the plastic deformation ability of metal materials under different stress states is not the same, and the stress-strain curve under compression is generally higher than that under tension [10]. In this study, the tensile test data were used as the input for the FEA model as the material properties of the nickel-based superalloy, which may explain why the experimental results were different from the simulation results. Also, the size of the CAD model of the origami structure was idealized in this study, and during the actual SLM process, the surface roughness of the lattice structure could be affected by the size of the laser spot, the quality of the powder bed and other factors, resulting in larger dimensional accuracy of the lattice structure, which may also cause the experimental value of quasi-static compression stress-strain curve to be higher than the FEA simulation results.

### 3.2.2 Damage and Deformation Mechanisms

The whole experimental process was recorded with a high-resolution camera during compression testing to better reveal the damage and deformation mechanisms of square origami structures with different wall thicknesses (50 µm, 75 µm and 100 µm) (Fig. 8).

At the beginning of compression (with compression displacement 1–2 mm and corresponding strain 3.3%–6.6%), the square origami structure was in a stage of linear growth of stress and strain. At this stage, the stress was evenly distributed in the folding area of the square origami structure. When the compression displacement reached 3 mm, the stress was mainly distributed in the folding area near the centre of the square origami structure. During the third stage of the compression process, the stress concentration in the folding area of the central position was very high, which led to instability in the central folding area of the square origami structure. The folding area began to crack, and finally fracture failure occurred.

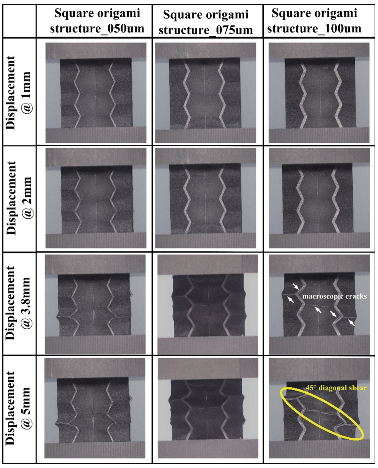



**Fig. 8.** Deformation behaviour of the square origami structure during quasi-static compression.

## 4 Conclusions

In this study we have developed a new square origami structure made of a nickel-based superalloy, manufactured with different wall thicknesses by the selective laser melting (SLM) process. Based on the results of finite element analysis (FEA) and experimentation, the main findings are as follows:

(1) The FEA simulation results showed that during the quasi-static compression process, the stress was evenly distributed in the folding area of the origami structure, indicating that this structure exhibited good load-bearing capacity.
(2) Before the square origami structure cracked and failed in the folding area, a plateau period occurred during the testing, indicating that this new square origami structure displayed good shock- and energy-absorption performance. In particular, the lattice structure with the thinnest wall (50 μm) was found to have the best energy-absorption performance under low stress. The nickel-based alloy used in the experiment was fairly brittle, however, which was also the main reason for the decreased stress found in the stress-strain curve.
(3) The results of the present study indicate that the SLM process may be used with advanced lattice structures made of nickel-based superalloys to accelerate the design of applications intended for lightweight structural performance.

**Funding.** This work was supported by the National Natural Science Foundation of China (Grant No. 52005295).

## References

1. Han, Q., Gu, H., Soe, S., Setchi, R., Lacan, F., Hill, J.: Manufacturability of AlSi10Mg overhang structures fabricated by laser powder bed fusion. Mater. Des. **160**, 1080–1095 (2018). https://doi.org/10.1016/J.MATDES.2018.10.043
2. Santosa, S., Wierzbicki, T.: Crash behavior of box columns filled with aluminum honeycomb or foam. Comput. Struct. **68**, 343–367 (1998). https://doi.org/10.1016/S0045-7949(98)00067-4
3. Ataee, A., Li, Y., Brandt, M., Wen, C.: Ultrahigh-strength titanium gyroid scaffolds manufactured by selective laser melting (SLM) for bone implant applications. Acta Mater. **158**, 354–368 (2018). https://doi.org/10.1016/j.actamat.2018.08.005
4. Maconachie, T., et al.: SLM lattice structures: Properties, performance, applications and challenges. Mater. Des. **183**, 108137 (2019). https://doi.org/10.1016/J.MATDES.2019.108137
5. Han, Q., et al.: Additive manufacturing of high-strength crack-free Ni-based Hastelloy X superalloy. Hast. Manuf. **30**, 100919 (2019). https://doi.org/10.1016/j.addma.2019.100919
6. Alomar, Z., Concli, F.: Compressive behavior assessment of a newly developed circular cell-based lattice structure. Mater. Des. **205**, 109716 (2021). https://doi.org/10.1016/j.matdes.2021.109716
7. Chen, F., Wang, Q., Zhang, C., Huang, Z., Jia, M., Shen, Q.: Microstructures and mechanical behaviors of additive manufactured Inconel 625 alloys via selective laser melting and laser engineered net shaping. J. Alloys Compd. **917**, 165572 (2022). https://doi.org/10.1016/J.JALLCOM.2022.165572
8. Leary, M., et al.: Inconel 625 lattice structures manufactured by selective laser melting (SLM): Mechanical properties, deformation and failure modes. Mater. Des. **157**, 179–199 (2018). https://doi.org/10.1016/J.MATDES.2018.06.010
9. Wang, Y., et al.: Numerical and experimental studies on compressive behavior of Gyroid lattice cylindrical shells. Mater. Des. **186**, 108340 (2020). https://doi.org/10.1016/J.MATDES.2019.108340
10. Crupi, V., Kara, E., Epasto, G., Guglielmino, E., Aykul, H.: Static behavior of lattice structures produced via direct metal laser sintering technology. Mater. Des. **135**, 246–256 (2017). https://doi.org/10.1016/j.matdes.2017.09.003

# Differences in Microstructural Aspects Between Die Pressing and Metal-Fused Filament Fabrication Using Powder Originating from Waste

J. G. Tirado González[1,2], A. Esguerra-Arce[1], L. K. Herrera[2], and J. Esguerra-Arce[1](✉)

[1] Industrial Engineering Department, CIMSER, Escuela Colombiana de Ingeniería Julio Garavito, AK.45 No. 205-59 (Autopista Norte), Bogotá, Colombia
johanna.esguerra@escuelaing.edu.co

[2] Departamento de Ingeniería Mecánica Y Mecatrónica, AFIS, Universidad Nacional de Colombia, Bogotá, Colombia

**Abstract.** It is important to study metal powder obtained from industrial waste given that its incorporation in the productive cycle is key to the sustainability of the cities of the near future, as well as to the use of sustainable manufacturing techniques. In this paper, an iron/iron oxide powder obtained by reduction of mill scale from hot deformation of low carbon steel was processed by two different techniques: die pressing and metal fused filament fabrication. Considering that microstructural features and the chemical composition are important factors in the mechanical properties of the final pieces, these two aspects were studied, both in the powders and in the final pieces. It was found that the presence of the polymer matrix during sintering of the piece fabricated by metal fused filament plays a key role in the process. This is because the hydrocarbons and $H_2$ produced during its decomposition lead to a further reduction in the remaining oxides, which in turn leads to an important difference with the pieces obtained by die pressing. Moreover, the dislocation density of the pieces is different, because the compaction of the powder by die pressing causes dislocation to multiply, while in the fused filament fabrication process there is no stage that involves dislocation multiplication.

**Keywords:** Metal-fused filament fabrication · Dislocation density · Mill scale · Die pressing

## 1 Introduction

Dislocations are the lineal defects that, along with the nature of the metallic bond, permit plastic deformation in metals. Under normal conditions, metals present dislocations. However, during plastic deformation at temperatures below that of recrystallization, dislocations multiply, leading to hardening of the material. The higher the dislocation density, the higher the hardness of the material. This means that, depending on the process used for the material, dislocation density affects its final mechanical properties.


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 67–76, 2023.
https://doi.org/10.1007/978-981-19-9205-6_7

Several manufacturing techniques exist for the fabrication of metal parts from powders obtained by milling [1], atomizing [2] or reduction from minerals [3]. This family of techniques is called powder metallurgy. A conventional method is die pressing, which consists of compacting the powders and sintering the green piece at temperatures around 70–80% of melting temperature, in order to activate diffusive movements of atoms and obtain intimate contact between the particles [4]. The parts obtained by this method can be very resistant, but their geometry is limited because of the molds used. However, since the 1980s some interesting manufacturing techniques have appeared, providing the opportunity to grow a piece layer by layer from a CAD (computer assisted design) model, which in turn allows pieces with complicated geometry to be obtained. These manufacturing techniques have been called *additive manufacturing* or *3D-printing* [5]. These techniques that allow metal parts to be processed from powders include *powder bed fusion (selective laser sintering* and *selective laser melting)*, which allows metal parts to be obtained directly [6]. Other techniques that allow metal parts to be obtained indirectly and inexpensively are *binder jetting* and *metal fused filament fabrication (MFFF)* [7].

MFFF consists of fabricating a filament composed of metallic powder embedded in a thermoplastic elastomer matrix. Typically, these filaments are 1.75 mm in diameter. Then, a 3D piece is obtained with the filament, as shown schematically in Fig. 1. After that, the piece is subjected to a thermal cycle where the polymer is eliminated and the metal particles are sintered, finally obtaining a 100% metal part [8]. The thermal cycles in this technique are longer than in powder metallurgy conventional techniques, because sufficient time is needed to eliminate the polymer without the powder collapsing. After the polymer elimination, however, the temperature must be increased quickly in order to reach the sintering temperature (70 – 80% of the melting temperature of the material from which the powders are derived), in order quickly to obtain coalescence of the powders through diffusion processes between the powders [9].

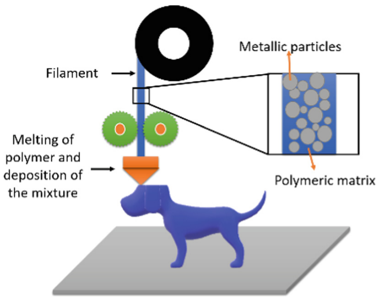



**Fig. 1.** Metal fused filament fabrication scheme

As has been published, during compaction of powders in die pressing, dislocations multiply [10]. This dislocation can remain after sintering if its density is not sufficient for recrystallization, making the final piece harder. However, to the best of the authors' knowledge, there are no studies that measure the dislocation density and changes during sintering process in metals processed by MFFF. Therefore, the aim of this study is to obtain an iron/iron oxide powder by partial chemical reduction of ground mill scale [3], and to process it by die pressing and MFFF, for purposes of comparison. The phases present were analyzed for comparison, as were the crystallite size and dislocation density in the reduced powders and sintered pieces after compaction (die pressing = DP) and printing by MFFF. This is valuable because of the great influence of these factors on the hardness of metal materials.

## 2 Methodology

### 2.1 Materials, Processes, and Characterizations

Mill scale from hot laminated low carbon steel was taken and dried for 24 h at 100 °C in order to eliminate moisture acquired during storage. Then, it was subjected to grinding for 119 h in a ball mill with a 5 L jar, using 400 mL of mill scale and 600 mL ball steel grinding bodies. The ground mill scale was characterized by X-ray diffraction (XRD) in a Brucker D8 Discover, with a Cu target (λ=1.54 Å). After that, the ground mill scale was subjected to a reduction treatment for 2 h at 700 °C using a Naberthrem™ furnace. The reductant gas used was $H_2$. Ar was used as carrier gas. Gas flow rate was fixed at 5.0 SCFH for each gas. The temperature of the powders was homogenized for 1 h before reduction. Once the powders were reduced, they were characterized by scanning electron microscopy (SEM) in a JEOL JSM-649 OLV Scanning Electron Microscope and XRD. The diffractograms were obtained with a RIGAKU (Dmax2100) diffractometer in the range 20–90° using Cu Kα, 1.54 Å (filter: Ni).

Green samples of 12.54 mm of diameter and 7 mm height were obtained by uniaxial compression with the reduced powders, using 160 kN force. Finally, the samples were sintered at 1050 °C for 1 h using a Naberthrem™ furnace in Ar atmosphere. $H_2$ flux was opened at 700 °C for 5 min in order to reduce any oxidized surface of the powders. Once the sintering process was finished and the samples were at room temperature, they were polished with sandpaper for evaluation by SEM and XRD (in the range 20–110°).

Meanwhile, TPE (thermoplastic elastomer) was mixed with polypropylene, stearic acid and the iron/iron oxide powder, making 50% volumetric powder and 50% volumetric TPE + polypropylene + stearic acid mix. 1.75 mm diameter filament was fabricated using a Filastruder™ extruder at 150 °C. After that, the filament was used to print pieces with 20 mm diameter and 0.8 mm height using the Creality Ender™ 3 printer. Finally, the pieces were subjected to the next thermal cycle, which consisted of the following: heating from room temperature to 180 °C for 5.3 h and holding at 180 °C for 1 h; heating to 400 °C for 7.4 h and holding at 400 °C for 7 h; heating to 500 °C for 7 h and holding at 500 °C for 0.4 h; and heating at 995 °C for 0.8 h ($H_2$ flux was opened at 700 °C for 5 min in order to reduce any oxidized surface of the powders) and holding at 995 °C for 1 h. A Naberthrem™ furnace was used for all the thermal treatments. Once the samples were at room temperature, they were polished with sandpaper for evaluation by XRD (in the range 20–110°).

### 2.2 Dislocation Density Measurement

Williamson and Smallman [11] developed an equation for calculating dislocation density (1) taking into account the microstrain in the lattice ($\eta$), the crystallite size (D) and the

Burger's vector (B), which is shown in Eq. 1. $\langle\eta^2\rangle^{1/2}$ refers to root mean square strain.

$$\rho = \sqrt{12}\langle\eta^2\rangle^{1/2}/(D \times B) \tag{1}$$

Williamson and Hall developed a method for calculating the lattice parameter (necessary for the calculation of Burger vector, $B = a/\sqrt{3}$ for BCC crystalline structure) and microstrain using the data from X-ray diffraction patterns [12].

According to the Scherrer method, crystallite size ($D$) contributes to the broadening of the diffraction peaks: an increase in the broadening peak indicates a decrease in D. The lattice strain also contributes to the broadening of the peaks. The contribution of crystallite size and microstrain are shown in Eqs. 2 and 3, where $\theta$ is the diffraction angle.

$$\beta = k\lambda/(D\cos\theta) \tag{2}$$

$$\beta_s = 4\eta\tan\theta \tag{3}$$

So, the width of the peak (without the instrumental broadening) is $\beta_{hkl} = \beta + \beta_s$, changing $\beta_{hkl}$ by FWHM (full width at half maximum) and multiplying both sides of the equation by $\cos\theta$, Eq. 4 is obtained.

$$\cos\theta \times FWHM = k\lambda/D + 4\eta\sin\theta \tag{4}$$

Using the peaks of XRD corresponding pattern, $\cos\theta \times FWHM$ and $4\sin\theta$ are calculated and the $\cos\theta \times FWHM$ vs. $4\sin\theta$ plot is obtained. Crystallite size is calculated by the intercept of the curve, and microstrain is calculated by the slope of the curve. Nelson Riley method [13] can be used to calculate the actual lattice parameter in order to obtain the Burger´s vector. First, Nelson-Riley function is calculated (Eq. 5) for each diffraction peak.

$$F(\theta) = \frac{1}{2}\left[\frac{(\cos\theta)^2}{\sin\theta} + \frac{(\cos\theta)^2}{\theta}\right] \tag{5}$$

Then, interplanar distance is calculated using Eq. 6.

$$d_{(hkl)} = \frac{\lambda}{2\sin\theta} \tag{6}$$

For each diffraction peak a lattice parameter is calculated using Eq. 7.

$$a = d_{(hkl)} \times \sqrt{h^2 + k^2 + l^2} \tag{7}$$

A plot of lattice parameter from Eq. 7 vs. Nelson-Riley function is drawn, and the actual lattice parameter is the intercept with y-axis.

## 3 Results and Discussion

Figure 2 shows the final pieces after both processes under study, demonstrating the suitability of the two processes for reincorporating the waste-derived powder by chemical reduction.

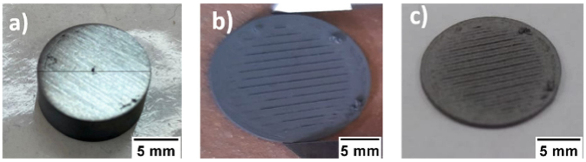



**Fig. 2.** (a) sintered sample obtained by die pressing, (b) printed part obtained by MFFF, (c) sintered part obtained by MFFF.

### 3.1 Ground and Reduced Mill Scale

Figure 3A depicts the XRD patterns of ground and reduced mill scale. As can be observed, mill scale is composed of the three iron oxides: wüstite (FeO), magnetite ($Fe_3O_4$) and hematite ($Fe_2O_3$). Contrary to reports by D. Shekhawat [14] there is no metallic iron in this mill scale. After reduction for 2 h (110), (200) and (211) peaks of metallic iron appear. However, wüstite and magnetite remain. This indicates a partial reduction of the powders, which occurs as follows [15]:

$$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$$

As the reduction occurs from outside to inside, the reduced powders consist of a core of iron oxide surrounded by iron. Figure 3b shows the morphology of the reduced particles. As can be seen, a porous surface is observed, which appears because of the reduction process when $H_2$ penetrates the particle, reacts with the iron oxides and produces $H_2O$, which leaves the particles. This is typical when iron is obtained by reduction from iron oxides [17].

Dislocation density was calculated for the iron in the powders (the metallic phase). Figure 4 depicts Williamson-Hall and Nelson-Riley plots for the reduced powders. As can be seen, the Williamson-Hall method depicts an $R^2$ of 0.82, demonstrating that it is appropriate for the calculation. Figure 8 summarizes crystallite size and dislocation density. This last value corresponds to $6.44*10^{10}$ cm/cm$^3$, which is not a typical value of annealed metals [10] and is instead typical of plastic-deformed iron [16]. When mill scale is formed, the steel is hot plastic-deformed, which actually causes dislocation multiplication. In the metal substrate, recrystallization occurs immediately, but it is possible for the iron oxides formed to retain the new dislocation density [18], which explains the high dislocation density in the reduced powder.

### 3.2 Die Pressing and MFFF Sintered Pieces

**Figure 5** shows the XRD patterns of sintered samples obtained by DP and MFFF. It can be observed that iron oxide remains after sintering. However, although DP sample shows magnetite and wüstite peaks, these appear in less quantity, while the MFFF piece shows only wüstite peaks. It should be borne in mind that the powders showed both oxides, magnetite and wüstite (Fig. 3). The lower quantity of peaks in sintered samples is because diverse crystallographic planes could be detected in the powder samples, due to the random orientation of grains, whereas in the bulk material, the order of crystallites of the material is less random [22]. XRD of the DP piece still shows peaks

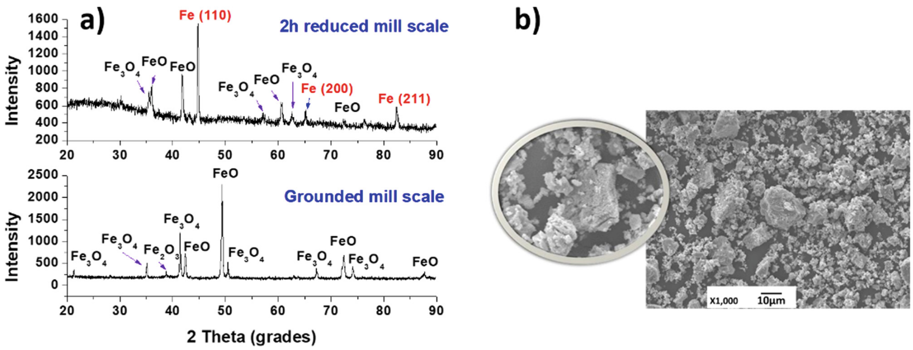



**Fig. 3.** (a) XRD patterns of mill scale when ground and chemically reduced for 2 h and (b) SEM image of reduced powder.

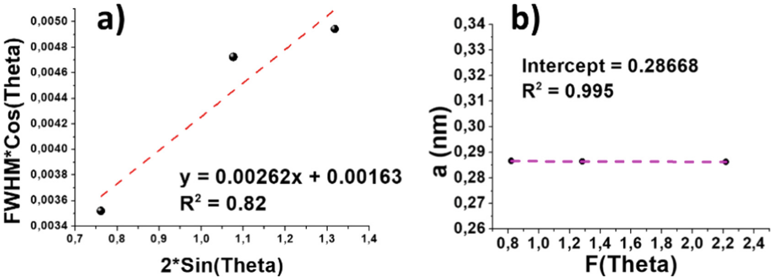



**Fig. 4.** (a) Williamson-Hall and (b) Nelson-Riley plots of metallic phase of the reduced powders.

corresponding to both oxides, wüstite and magnetite (as corroborated by part b of Fig. 5), whereas the XRD of the MFFF piece only shows wüstite peaks. This can be explained by the differences in the processes during sintering. Specifically, in DP the powders are in intimate contact after compaction and surrounded by Ar gas during sintering, however in MFFF the powders are surrounded by the polymer matrix during sintering. In MFFF they also suffer important changes during the thermal treatment; firstly, the TPE degrades, then PP degrades, which puts the powders in contact for sintering. The fact that these polymers are present changes the dynamics during reduction. $H_2$ is produced during the degradation of the polymers, as well as carbon. The $H_2$ produced is able to reduce the oxides that remain in the powders, producing water, and the carbon produced then reacts with the water. This is turn produces $CO_2$ and more $H_2$, which continuously takes part in further reduction of the iron oxide, leading to the formation of only FeO in the sintered samples [19]. In addition, as explained by Murakami and Kasai [20], the iron oxide is reduced by hydrocarbon gases generated from the polymer, as well as $H_2$.

Figures 6 and 7 depict the Williamson-Hall and Nelson-Riley plots of DP and MFFF samples. The results of the dislocation density calculation are shown in Fig. 8. Some authors report dislocation density with $R^2$ of Williamson-Hall plots less than 0.76 [21] which indicates that the results here are reliable. As can be seen, the dislocation density of sintered samples obtained by die pressing is higher than that of the powders. This is

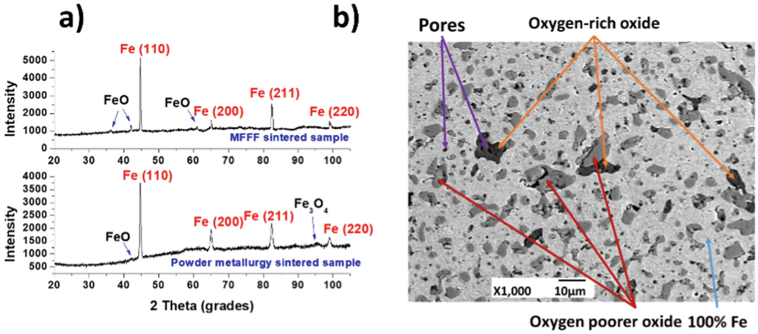



**Fig. 5.** (a) XRD patterns of sintered pieces obtained by die pressing and MFFF and (b) SEM image of die pressed sintered piece

explained because during compaction, yield strength of the powders are overcome. This leads to dislocation multiplication [10]. As sintering is carried out at temperatures higher than recrystallization temperature, some recrystallization occurs, which is evident by the reduction in crystallite size shown in Fig. 8. However, dislocation density remains high. With respect to MFFF, it can be seen that dislocation density is not as high as in the case of die pressing, in fact, it is in the same order of magnitude as the powder. This is because, for MFFF, the powders are used directly from the reduction process to fabricate the filament and build the part, which does not lead to dislocation multiplication. With respect to the crystallite size, it can be observed that this diminishes from powder to bulk piece after printing and sintering. This could be because of the formation of the new iron phase for the chemical reduction that occurs during sintering. This new iron phase presents low grain size, and so the average crystallite size of the material diminishes.

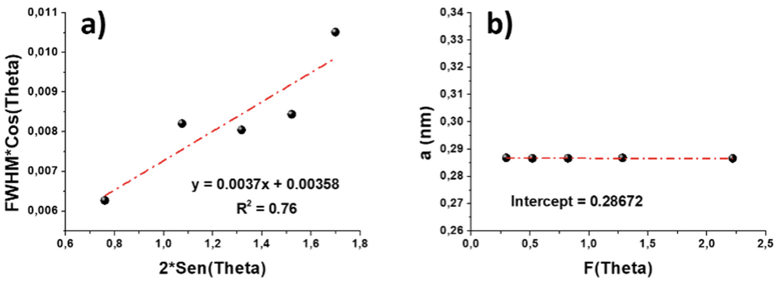



**Fig. 6.** Williamson-Hall and Nelson-Riley plots of sintered samples obtained by die pressing

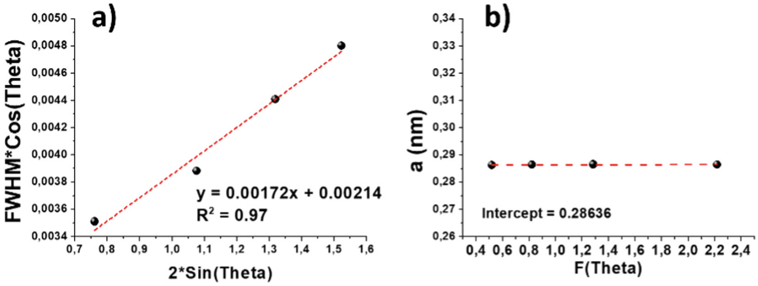



**Fig. 7.** Williamson-Hall and Nelson-Riley plots of sintered samples obtained by MFFF

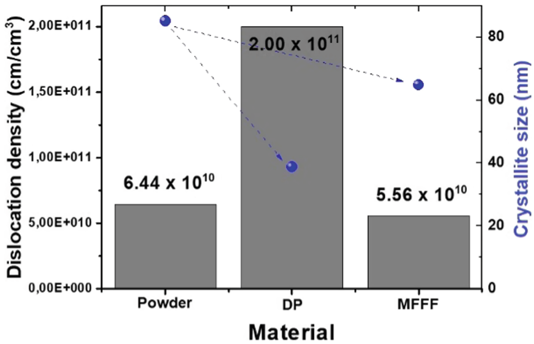



**Fig. 8.** Dislocation density (bars) and crystallite size (dots) of the materials under study

## 4 Conclusions

The suitability of iron/iron oxide composite powder obtained by partial chemical reduction of mill scale produced during hot deformation of low carbon steel, to produce metal-fused filament fabrication parts was studied, comparing these with die pressed pieces. It was found that:

- The powder is suitable for obtaining parts using metal-fused filament fabrication technique.
- The presence of the matrix polymer in the samples affects the sintering process, leading to an additional reduction process which transforms the $Fe_3O_4$ phase in the piece into FeO oxide.
- The dislocation density does not suffer changes in the transition from the powder to the piece after printing and sintering, because there is no stage in the process that involves dislocation multiplication. This is not the case for die pressing, where dislocation multiplies during compaction of the powders. It means that die pressing leads to more resistant pieces when compared with metal fused filament fabrication.

Future research will focus on studying the costs of the entire processes to assess the most appropriate way to recover the by-product.

## References

1. Pulido-Suárez, P.A., Uñate-González, K.S., Tirado-González, J.G., Esguerra-Arce, A., Esguerra-Arce, J.: The evolution of the microstructure and properties of ageable Al-Si-Zn-Mg alloy during the recycling of milling chips through powder metallurgy. J. Mater. Res. Technol. **9**(5), 11769–11777 (2020)
2. Fedina, T., Sundqvist, J., Powell, J., Kaplan, A.F.H.: A comparative study of water and gas atomized low alloy steel powders for additive manufacturing. Addit. Manuf. **36**, 101675 (2020)
3. Tirado González, J., Reyes Segura, B.T., Esguerra Arce, J., Bermúdez Castañeda, A., Aguilar, Y., Esguerra Arce, A.: An innovative magnetic oxide dispersion-strengthened iron compound obtained from an industrial byproduct, with a view to circular economy. J. Clean. Prod. **268**(20), 122362 (2020)
4. Sankhla, A.M., Patel, K.M., Makhesana, M.A., Giasin, K., Pimenov, D.Y., Wojciechowski, S., Khanna, N.: Effect of mixing method and particle size on hardness and compressive strength of aluminium based metal matrix composite prepared through powder metallurgy route. J. Mater. Res. Technol. **18**, 282–292 (2022)
5. Gong, G., Ye, J., Chi, Y., Zhao, Z., Wang, Z., Xia, G., Du, X., Tian, H., Yu, H., Chen, C.: Research status of laser additive manufacturing for metal: a review. J. Mater. Res. Technol. **15**, 855–884 (2021)
6. Qbau, N., Nam, N.D., Hien, N.T., Ca, N.X.: Development of light weight high strength aluminum alloy for selective laser melting. J. Mater. Res. Technol. **9**(6), 14075–14081 (2020)
7. Roshchupkin, S., Kolesov, A., Tarakhovskiy, A., Tishchenko, I.: A brief review of main ideas of metal fused filament fabrication. Mater. Today **38**(4), 2063–2067 (2021)
8. Singha, P., Ballaa, V.K., Tofangchic, A., Atrea, S.V., Katea, K.H.: Printability studies of Ti-6Al-4V by metal fused filament fabrication ($MF^3$). Int. J. Refract. Met. Hard Mater. **91**, 105249 (2020)
9. Wagner, M., Hadian, A., Sebastian, T., Clemens, F., Schweizer, T., Rodriguez-Arbaizar, M., Carreño-Morelli, E., Spolenak, R.: Fused filament fabrication of stainless steel structures - from binder development to sintered properties. Addit. Manuf. **49**, 102472 (2022)
10. Kovalchenko, M.S., Hrebenok, T.P., Brodnikovskii, N.P., Rogozinskaya, A.A.: Theory and technology of forming process: features of brittle material powder compaction during pressing. Powder Metall. Met. Ceram. **55**(5–6), 259–269 (2016)
11. Williamson, G.K., Smallman, R.E.: Dislocation densities in some annealed and cold-worked metals from measurements on the X-ray debye-scherrer spectrum. Philos. Mag., 34–46 (1955)
12. Mote, V.D., Purushotham, Y., Dole, B.N.: Williamson-Hall analysis in estimation of lattice strain in nanometer-sized ZnO particles. J. Theor. Appl. Phys. (6), 6–14 (2012)
13. Tsai, D.S., Chin, T.S., Hsu, S.E., Hung, M.P.: A simple method for the determination of lattice parameters from powder X-ray diffraction data. Mater. Trans. JIM (30), 474–479 (1989)
14. Shekhawat, D., Gautam, N., Banerjee, M.K., Patnaik, A.: Investigate the reduction of mill scale with low grade coal through solid gas reactor. Mater. Today (44), 4801–4808 (2021)
15. Jikar, P.C., Dhokey, N.B.: Overview on production of reduced iron powder from mill scale waste. Mater. Today (44), 4324–4329 (2021)
16. Tanaka, Y., Masumura, T., Tsuchiyama, T., Takaki, S.: Effect of dislocation distribution on the yield stress in ferritic steel under identical dislocation density conditions. Scr. Mater. **177**, 176–180 (2020)
17. Sen, R., Pandel, U.: Closed crucible reduction of lump powdered mill scale or iron ore by coal: The sequential methodology and mechanism for optimization of process parameters. Adv. Powder Technol. (31), 3760–3773 (2020)

18. Szot, K., Rodenbücher, C., Bihlmayer, G., Speier, W., Ishikawa, R., Shibata, N., Ikuhara, Y.: Influence of dislocations in transition metal oxides on selected physical and chemical properties. Crystals **8**(241), 1–77 (2018)
19. Assefi, M., Mofarah, S.S., Maroufi, S., Nekouei, R.K., Wang, W., Kert, E., Sahajwalla, V.: Regeneration of hydrogen through thermal micronisation of end-of-life polymers for sustainable reduction of iron Oxide. Fuel Process. Technol. **226**, 107038 (2022)
20. Murakami, T., Kasai, E.: Reduction mechanism of Iron Oxide–Carbon composite with Polyethylene at lower temperature. ISIJ Int. **51**(1), 9–13 (2011)
21. Baghdadi, A.H., Rajabi, A., Mohamad, N.F., Sajuri, Z., Omar, M.Z.: Effect of post-weld heat treatment on the mechanical behavior and dislocation density of friction stir welded Al6061. Mater. Sci. Eng. A (754), 728–734 (2019)
22. Behroozibakhsh, M., Hajizamani, H., Shekofteh, K., Otadi, M., Ghavami-Lahiji, M., Faal Nazari, N.S.: Comparative assessment of the crystalline structures of powder and bulk human dental enamel by X-ray diffraction analysis. J. Oral Biosci. **61**, 173–178 (2019)

# Lightweight Tooling for Concentric Collet Drilling Templates

Xiaoji Zhang[1], Rossitza Setchi[1](✉), Khaled Giasin[2], Heng Gu[3], Quanquan Han[4], Michael Ryan[1], and Andrew Hopkins[1]

[1] Cardiff School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
setchi@cardiff.ac.uk

[2] School of Mechanical and Design Engineering, University of Portsmouth, Portsmouth PO1 3DJ, UK

[3] School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China

[4] Centre for Advanced Jet Engineering Technologies (CaJET), Centre for Additive Manufacturing, School of Mechanical Engineering, Key Laboratory of High Efficiency and Clean Mechanical Manufacture, Shandong University, Jinan 250061, China

**Abstract.** This paper aims to meet clear business demand for lighter operational jigs and tools by reducing the overall weight of the concentric collet drilling templates using alternative lightweight materials and topology optimization techniques. The template structure was optimized by numerical modelling to reduce the mass and maintain relative strength. A cycle test that simulates the actual working conditions of the templates was conducted to understand the deformation and wearing during and after their usage. The simulation results indicate the challenges between reducing the mass and maintaining the stiffness of the drilling template. The hole size in each alternative aluminum template increased after 10,000 testing cycles; For harder materials like Al7075, the hardness of the borehole increased due to its high strength, to resist extending force from the collet. Whereas, for the materials with lower hardness like Al5083, the borehole hardness reduced after the cycle tests due to its low strength. The borehole surface roughness in the template increased due to wear caused by the horizontal pressure and vertical contact with the collet, which would severely increase the friction and reduce the lifetime of the template.

**Keywords:** Drill jig template · Aluminum hardness · Friction and wearing damage

## 1 Introduction

A jig is a type of tool used to control the location and/or motion of another tool. It is a work-holding device that holds, supports, and locates the workpiece and guides the cutting tool for a specific operation [1]. The primary purpose of a jig is to provide repeatability, accuracy, and interchangeability in the manufacturing of products [2]. Drilling jigs such as those used in creating holes in aerospace structures provide methods for correctly locating the workpiece with respect to the cutting tool [3]. Compared to conventional


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 77–87, 2023.
https://doi.org/10.1007/978-981-19-9205-6_8

hand methods drill jigs help in drilling, reaming, and tapping holes at a higher speed with great accuracy [4]. Millions of holes are drilled (single or multi-stage operations) into aircraft structures and the positioning of the drill is provided by drilling templates. These templates, manufactured mainly from wrought 7075 Aluminum machined plates, have proven effective over time. However, there is also a lack of knowledge regarding how long a drill jig lasts and its accuracy over its operational lifetime which is important information. As demand from the aerospace industry for high-performance tooling is increasing, the use of lightweight tooling that would result in a reduction of the handling time, number of operators, and lower risk of injuries potentially provides a good market opportunity to introduce new materials/manufacturing technologies into the tool making process and market.

The structural optimization of drilling jigs was investigated mainly via modelling simulations or Computer-Aided Design (CAD) due to the low cost and high speed of such methods [5–7]. There is also research interest in optimizing the material used for manufacturing jigs. Jigs and fixtures are typically made of hardened materials to avoid frequent damage and to resist wear, including soft-cast steel, cast iron, die steel, steel, high speed steel, nickel-chrome steel, bronze, plastic material etc. [8–10].

The objective of this paper is to demonstrate how to reduce the overall weight of the concentric collet drilling templates by using alternative lightweight materials and topology optimization techniques. Two aspects were considered, including optimizing the structure of the templates by reducing their volume and applying lighter materials. Numerical modelling was used to optimize the template structure for reducing the mass and maintaining relative strength. Cycle tests simulating actual practice were carried out on the alternative templates to understand their deformation and wear behavior during and after usage.

## 2 Modelling and Experimentation

### 2.1 Modelling

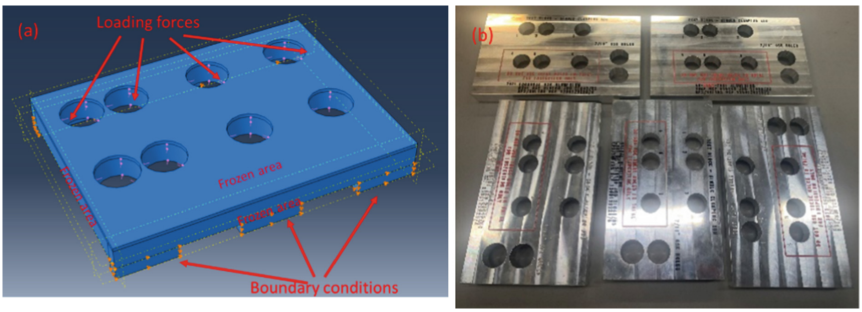



**Fig. 1.** Modelling of the templates (a) and alternative Aluminum templates (b).

To achieve a better understanding of the response of the hole dimension change on the existing drilling templates against various loading conditions, Finite Element Analysis

(FEA) modelling was carried out for simulation. Al7075 was used as the raw material for the modelling. The template dimension was 363 mm × 180 mm × 20 mm. The collet hole was 34.93 mm, and the mass is 3.35 kg. 1500 N radial load was applied on each hole and the mass reduction was 30% off, 40% off, and 50% off, respectively. Boundary conditions stipulating that all the legs were fixed were also applied to the modelling as shown in Fig. 1(a).

## 2.2 Template Design and Materials

**Table 1.** Average hole diameters on each template by the coordinate measuring machine (CMM) (mm).

| Material | Al7075 | | Al7072 | | Al6082 | |
|---|---|---|---|---|---|---|
| Hole No | 1 | 2 | 1 | 2 | 1 | 2 |
| Diameter | 35.020 | 35.021 | 35.025 | 35.022 | 35.010 | 35.011 |
| Material | Al5083 | Unidal Al | | | | |
| Hole No | 1 | 2 | 1 | 2 | | |
| Diameter | 35.015 | 35.014 | 35.011 | 35.009 | | |

It was considered more beneficial to replace high-cost Aluminum 7075 with a cheaper and easier to machine Aluminum material. Therefore, the templates of 5 different Aluminum materials in the tests were shown in Fig. 1(b), including Al7075 (the current material of used templates), Al7021, Al6082, Al5083, Unidal Al. Two adjacent holes on each template were measured as candidates for the tests as shown in Table 1. All hole diameters were under H8 tolerance (0–0.039 mm), which is technically required. The thickness of all templates was 20 mm.

## 2.3 The Machine Design, Cycle Tests, and Measurements

To simulate the actual working conditions of drilling holes guided by the drilling jigs, cycle tests were conducted on the templates. In the tests, The Advanced Drilling Unit (ADU) will move down and insert into the hole of the drilling jig, then the collet will expand to be fixed by the hole for the following drilling. After a period of extension (5 s in this test), the collet closed and the ADU then moved back to the original position. A test rig was developed to control the movement and operation of the ADU simultaneously and fully automatically, as presented in Fig. 2 (a). An actuator, which controls the movement of the ADU in the z-direction, was connected to the ADU. Two relays were added to the system, allowing the extension and retraction of the actuator to be controlled. A solenoid was used to switch on/off the expansion of the ADU, which was activated by air pressure of 5 bar. An Aluminum frame was built to house all the controlling components and two guide rails were installed to stabilize the movement of the ADU. By adjusting the cycle frequency and ADU dwelling time, this automatic hole expansion testing rig is capable

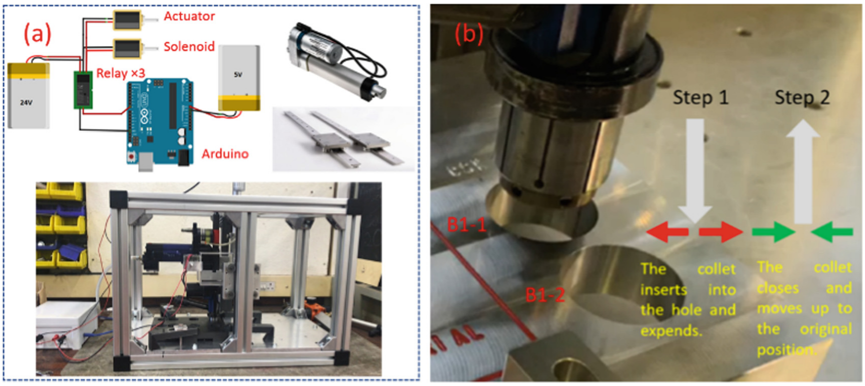



**Fig. 2.** Cycle test hardware and mechanism, (a) automatic hole expansion testing rig with actuator and guide rail, (b) the schematic.

of repeating thousands of testing cycles within hours. The cycle test schematic is shown in Fig. 2 (b).

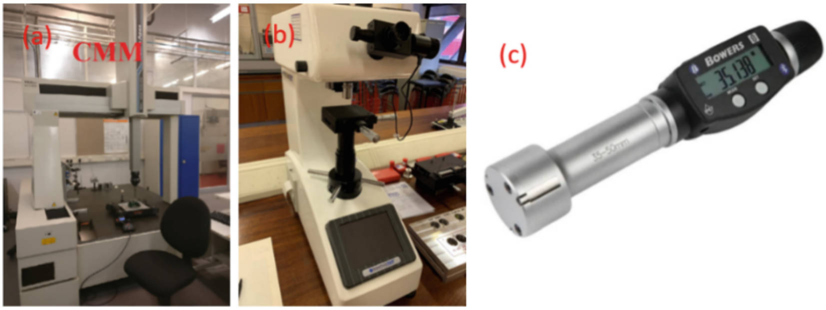



**Fig. 3.** Measurement devices, (a) CMM, (b) the hardness tester, and (c) the bore micrometer for intermittent measurement.

During the testing process, the ADU was controlled with a frequency of 5s open and 5s closed. Between each cycle, the ADU would lift from the hole and go down into the hole again to simulate the drilling cycles. According to measurement, the collet diameter is approximately 34.93 mm when being closed and approximately 35.27 mm when extending. For tests on a template, 10,000 cycles were repeated on each tested hole. Intermittent measurements were completed at 1000, 3000, and 6000 cycles to analyze the transformation during cycle tests. Figure 3 shows the device used to measure hardness and the size of the holes before and after the cycle tests to understand the impacts of these tests on the templates.

# 3 Results and Discussion

## 3.1 Numerical Modelling

Topology optimization was conducted to reduce the weight of the concentric templates. Two topology strategies were considered as shown in Fig. 4. In Fig. 4. (1), if no preserved regions were selected, the optimization will take materials from any area in the template, which would cause some difficulty in maintaining an adequate shaper for the optimized template. By contrast, from Fig. 4(b), some regions were preserved, and the topology optimization model removed materials from critical regions such as the base supports, which would be selected in the simulation.

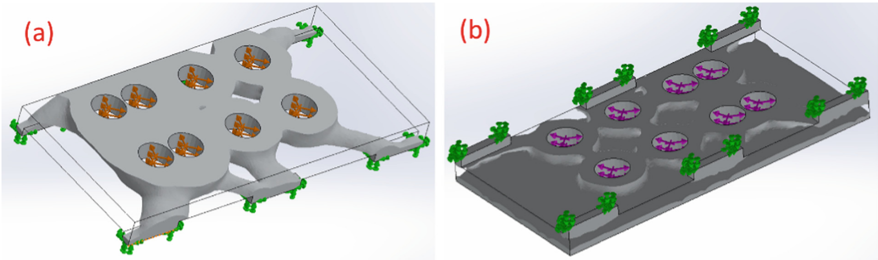



**Fig. 4.** Topology strategy on the templates by FEM modelling, (a) no preserved regions, and (b) preserved regions.

The mass reduction was from 30% to 50%. Several topology optimized models were developed as shown in Fig. 5. Some examples of Al7075 were given below, showing the topology optimization process undertaken to maximize the stiffness/weight ratio with different weight reduction rates for template CAD models.

Based on the simulation results shown in Table 2, it can be concluded that with the reduction of mass percentage, the maximum displacement would increase. In addition, the optimized design will differ when applying different additional loading and boundary conditions, which depends on the specific requirement of each template during the manufacturing or handling process.

It can also be noted from the modelling results that, even after applying additional loading conditions, the maximum displacement is still quite low (less than 1 $\mu$m) compared with the hole dimensions (the diameter is 34.93 mm), indicating that the template would maintain the dimensions of the jig holes even after getting 50% mass reduction, since the deformation is still within the elastic deformation range.

## 3.2 Cycle Test Results of Alternative Aluminum Templates

The final diameters after cycle testing were measured by both bore micrometer and CMM machine. Cycle tests were done on one hole of Al7075 (B1), Al7072 (B2), Al5083 (B4), and Unidal Al (B5); on both holes of Al6082 (B3) (for comparison of insertion/extraction cycles and non-insertion cycles). The hole adjacent to the Unidal Al hole that was tested was also measured to gain an understanding of how the non-cycled hole was impacted.

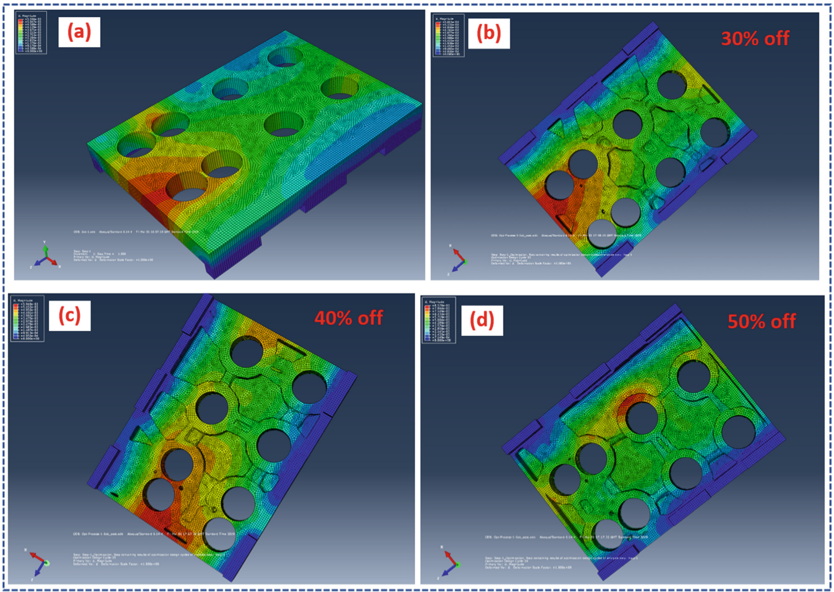



**Fig. 5.** Topology optimized template of Al7075 with (a) 0%, (b) 30%, (c) 40% and (d) 50% weight reduction.

**Table 2.** The results of mass reduction and displacement after simulation.

| Mass reduction | Maximum displacement |
|---|---|
| 0% (3.35 kg) | 0.551 μm |
| 30% (3.35 kg → 2.35 kg) | 0.582 μm |
| 40% (3.35 kg → 2.01 kg) | 0.595 μm |
| 50% (3.35 kg → 1.68 kg) | 0.858 μm |

Figure 6 shows the results for all diameters after cycle tests as measured by the micrometer. The diameter increased gradually during cycle tests due to both horizontal extending force and vertical friction. From Table 3, the deformation rate of each hole was calculated, which gives an insight into the relationship between deformation and hardness. The hole diameter increased after cycle tests and the rate of increase was much higher if the hardness of the material is low. For harder materials, for example, Al7075, the rate of increase was low. Al6082 and Al5083 have relatively low hardness and their rate of increase is relatively high. The shrinkage rate of the non-tested hole (Unidal Al - 2) is much higher than the rate of increase of the tested hole (Unidal Al - 1) even though there is a 5mm-thick wall between the two holes.

Hardness tests were conducted on the edge and the wall of each tested hole respectively (shown in Fig. 7), to understand how the material was hardened by the cycle tests. Results were shown below in Fig. 8. The indentation loading was 5 kg using a Vickers

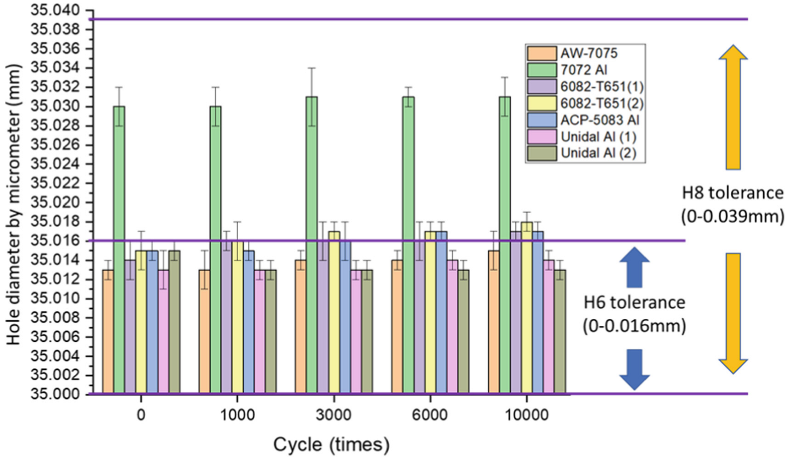



**Fig. 6.** Changing hole diameters (mm) from 0 to 10,000 test cycles for a range of Al alloys.

**Table 3.** The deformation rate of each hole after 10,000 test cycles (" +" presents extending and "–" presents shrinkage of the hole size).

| Materials | Al7075 | Al7021 | Al6082–1 | Al6082–2 |
|---|---|---|---|---|
| Hardness (HV) | 182.3 | 125.4 | 113.8 | 113.8 |
| Increasing rate | +0.0057% | 0.0% | +0.0086% | +0.0086% |
| Materials | Al5083 | Unidal Al-1 | Unidal Al-2 | |
| Hardness (HV) | 85.0 | 139.9 | 139.9 | |
| Increasing rate | +0.0057% | +0.0029% | −0.0086% | |

indenter. The distance between the central point of the indentation and the edge is about 0.2 mm.

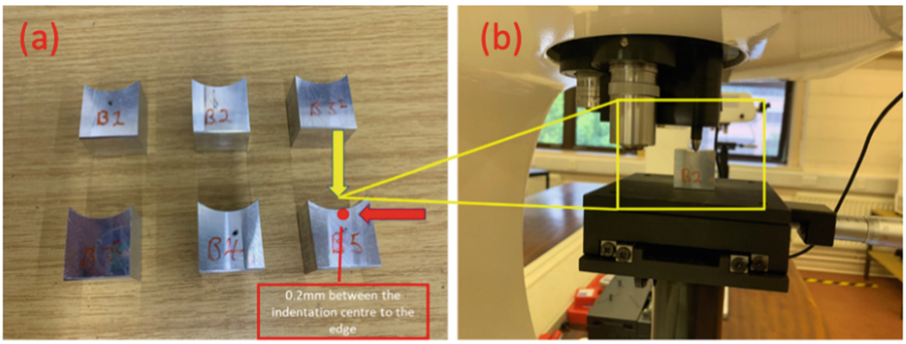



**Fig. 7.** Hardness tests on the edge and the wall of the hole.

For hardness tests on the edge, as the indentation was close to the edge, some materials were pushed down due to the plastic deformation, therefore, the size of the indentation would be larger than normal, which led to lower results than normal. Therefore, the tested results shown in the table and figure can only be used for information, rather than accurate results.

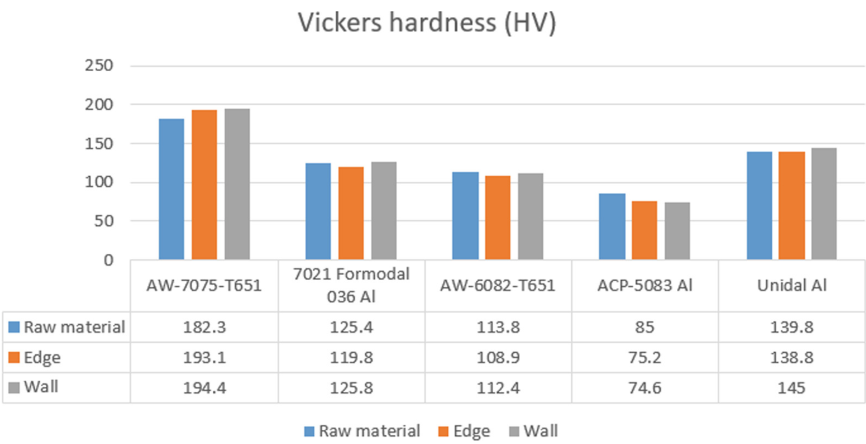



**Fig. 8.** Vickers hardness results.

For the hardness of the sidewall, it can be seen from the figure above that, for the materials with relatively higher hardness, for example, Al 7075 and Unidal Al, the hardness results of the sidewall were higher than the raw materials. For the materials of medium hardness like Al 7021 and Al 6082, the hardness of the sidewall did not exhibit major differences compared to the raw materials. For the relatively softer material, Al 5083, the result was even lower than for the raw material.

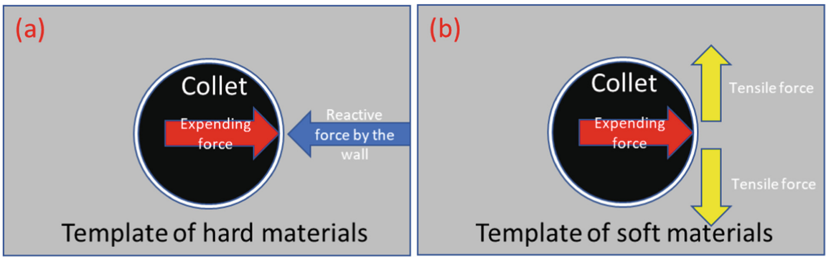



**Fig. 9.** The schematic of forces from the collet extending to different materials, (a) for hard materials and (b) for soft materials.

For the harder materials, for example, Al7075, when the extending force worked at the sidewall, the solid material would resist the force and the sidewall was compressed due to its relatively high strength, as shown in Fig. 9(a). The material of the sidewall was hardened by the pressure, resulting in increased density and hardness.

Compared with the hard materials, when the extending force acted on the sidewall of Al5083, the material is not able to resist the force due to its lower strength, as shown in Fig. 9(b), which became the tensile force to the sidewall. Due to the tensile stress, the density of the sidewall would reduce, and the hardness goes down as well. In this case, the deformation is still in the elastic range, which can also be proven by the simulation results of low-strength materials/structures in Sect. 3.1.

For medium hardness materials, the sidewall is both compressed and stretched from the extending force of the collet. Therefore, the hardness of the sidewall did not experience a big change after the cycle tests.

### 3.3 Damage Due to Friction and Wearing

During cycle tests, it was found that inserting and extracting the collet will increase wearing between the hole wall and the collet. Specifically, when the collet opens, it has both vertical displacement and horizontal extension. The vertical displacement will lead to friction, which can be increased by horizontal extension as shown in Fig. 10(a). This friction will severely damage the wall quality and impact the circularity as shown in Fig. 10.(b). This effect has more influence on the hole size than the extending transformation by horizontal extending force. Therefore, wearing tests to understand the tribological properties of the material are worth considering, which is significant for optimizing the cycle test parameter and choosing the appropriate material for the practical drilling tasks.

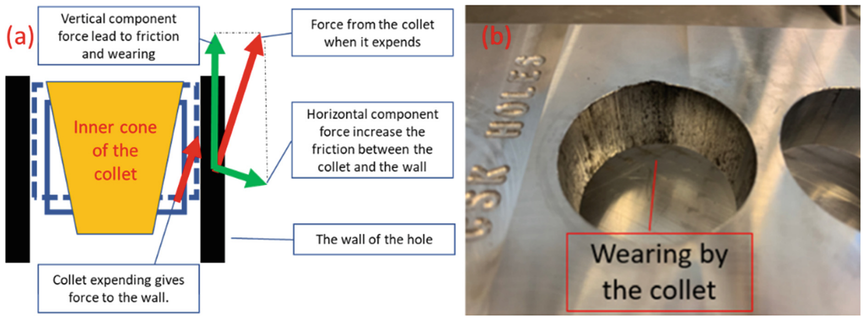



**Fig. 10.** (a) Analysis of the friction between the collet and the hole, (b) demonstration of wearing of the jig.

## 4 Conclusions

In this paper, the structures of the templates were optimized by numerical modelling to reduce the mass. The simulation results highlight the challenges between reducing the mass and increasing the strength of the templates. The alternative lightweight materials and topology optimization techniques can effectively reduce the overall weight of the templates, while maintaining performance. Five alternative Aluminum materials were tested. The diameter of the hole increased after cycle tests; however, all increased diameters were under H8 tolerance after 10,000 test cycles. For those materials with higher hardness like Al 7075, the hardness of the sidewall of the hole increased due to its high strength to resist the extending force from the collet. Whereas, for lower hardness materials like Al5083, the hardness of the wall reduced after the cycle tests due to its low strength. Wearing from the horizontal pressure and vertical friction between the collet and the hole damaged the surface of the hole, resulting in a rough surface, which would severely increase friction and reduce the lifetime of the templates. The modelling and experiments in this paper confirm that the mass of the jigs can be significantly reduced, as well as the cost of the associated materials as the currently used Al7075 can be replaced by softer, cheaper Al5083 while still maintaining performance during the tests. The cycle test that simulates the actual working conditions of drilling jigs can also be applied to similar tooling to identify any potential performance improvements and cost reductions. Nevertheless, the cycle test did not include unexpected knocks and wearing that would occur by manual operations during practice, which would cause more damage to the templates.

**Acknowledgement.** This research was conducted within the framework of a collaborative project between Airbus, Cardiff University and Swansea University as part of the ASTUTE 2020$^+$ Operations, which support manufacturing companies across Wales and which are part-funded by the European Regional Development Fund through the Welsh Government and the participating Higher Education Institutions. The authors wish to recognize the invaluable input of Mr. Malcolm Cook, Airbus Process Technology Leader (APTL), who gave technical support and guidance during the research.

## References

1. Hoffman, E.: Jig and Fixture Design. Cengage Learning, Boston (2012)
2. Pandit, G.P., Shinde, R.V., Patil, S.B., Amale, S.B.: Modelling and analysis of drilling jig for mounting casing of electric motor. International Journal of Innovative Technologies **3**(10), 1838–1844 (2015)
3. Radhwan, H., Effendi, M.S.M., Rosli, M.F., Shayfull, Z., Nadia, K.N.: Design and analysis of jigs and fixtures for manufacturing process. IOP Conf. Ser. Mater. Sci. Eng. **551**, 012028 (2019)
4. Vathare, S., Gombi, S.L., Katgeri, D.M.,: Design and analysis of drill jig for head and cover part of the actuator. Int. J. Eng. Res. Technol. **3** (2014)
5. Mohammed, A.J., Tariq, M.: Design and Analysis of Drill Jig for a Shaft Using ANSYS. Internations Journal of Scientific Engineering and Technology Research **2**(18), 2059–2066 (2013)
6. Kumar, A.S., Fuh, J.Y.H., Know, T.S.: An automated design and assembly of interference-free modular fixture setup. Comput. Aided Des. **32**(10), 583–596 (2000)
7. Cho, C.S., Choi, E.H., Choe, J.R., Lim, O.K.: Topology and parameter optimization of a foaming jig reinforcement structure by the response surface method. Comput. Aided Des. **43**(12), 1707–1716 (2011)
8. Reddy, K.R., Babu, S.R., Babu, A.V.: Design and analysis of drill jig at variable materials. International Research Journal of Engineering and Technology **3**(06), 2022–2029 (2016)

9. Kumari, N.B.V.L., Kumar, G.P.: Design and analysis of indexing type of drill jig. Journal of Mechanical and Civil Engineering **12**(2), 46–51 (2015)
10. Korsakov, V.: Fundamentals of Fixture Design. MIR Publication, Moscow (1989)

# Aspects of a Sustainability Focused Comparison of the Wire Arc Additive Manufacturing (WAAM) and the Laser Powder Bed Fusion (LPBF) Process

Johanna Wurst[1,3](✉), Timon Steinhoff[2,3], Iryna Mozgova[1], Thomas Hassel[2], and Roland Lachmayer[1]

[1] Institute of Product Development, Leibniz University Hannover, An der Universität 1, 30823 Garbsen, Germany
wurst@ipeg.uni-hannover.de
[2] Institute of Materials Science, Leibniz University Hannover, An der Universität 2, 30823 Garbsen, Germany
[3] School for Additive Manufacturing (SAM), Garbsen, Germany

**Abstract.** Determining whether additive manufacturing processes for metallic materials offer a high potential regarding the ecological sustainability dimension not only depends on the materials used, it is also significantly influenced by the individual process chain. Within the the product life cycle, the production phase is decisive for the impact until the end of life. By analyzing this time- and resourceintensive phase, it is possible to make decisive conclusions concerning the characteristics of the product itself in the preceding phase of product development. Moreover, as part of innovative new manufacturing processes, the question arises as to how these can be optimized in terms of diverse sus-tainability aspects. In order to be able to formulate such statements, detailed process analysis is required first, to identify specific hotspots within the phases as well as to refer to the individual parameters or parameter sets of the manufacturing process examined.

In this paper, two processes, the Laser Powder Bed Fusion (LPBF) and the Wire Arc Additive Manufacturing (WAAM) process, are compared with each other regarding their environmental impact. Based on the results of a life cycle assessment according to ISO 14040ff., phaserelated impacts are calculated, processspecific hotspots are identified and statements regarding ecological sustainability potentials within the process chains are deduced.

**Keywords:** Additive manufacturing · Life cycle assessment · Sustainability analysis

## 1 Introduction

As products become increasingly individualised in limited quantities, the economic feasibility, environmental impact as well as the resulting effects on the entire product life cycle have a growing influence on the product itself and its production processes.


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 88–97, 2023.
https://doi.org/10.1007/978-981-19-9205-6_9

Analysing process chains of each manufacturing technique delivers an individual way to spot and search for potential characteristics and differences in these aspects mentioned before [2]. As the environmental assessment of additively manufactured products primarily focuses on the comparison of additive with conventional manufacturing [2], an environmental side-by-side assessment of two metallic additive manufacturing processes will be conducted in this publication. Using material flow nets, the Laser Powder Bed Fusion (LPBF) and Wire Arc Additive Manufacturing (WAAM) processes are compared in a "cradle-to-gate" approach in the context of a life cycle assessment. The results of this study, exemplified by a demonstrator made of aluminium, are used as a preliminary study for the following investigation of the product's performance during its use phase.

## 2 Additive Manufacturing of Metals

Additive manufacturing processes are clustered in seven categories as per ISO/ASTM standards [3]. For metals these can be further differentiated in many ways, firstly there is the feedstock material used during the process. This could be powder, wire or in rare cases thin sheets of metal. Then secondly, the form of binding of the material is crucial to form a layer. Within the research network of the School for Additive Manufacturing (SAM), wire-based as well as powder bed-based metallic additive manufacturing processes are investigated. Therefore, the environmental assessment of the LPBF and the WAAM processes provides an opportunity to conduct a reasoned comparison of different manufacturing technologies using the same material. Powders and wires can be molten fully and then solifidicatite as new layer. Powders can also be bonded through a binding agent or sintering processes. Sheets of metal are mostly cut into shape and then the foregoing layer is applicated in a materially cohesive way. Another important aspect is the way to transfer the energy needed to melt the material each layer, with lasers, electron beams or electric arcs [4].

### 2.1 Laser Powder Bed Fusion Process

Combinations of these aspects yield the different available MAM processes. The common most industrially used MAM process is the Laser Powder Bed Fusion process or short LPBF [5]. Here a recoater with rolls or sharp blades levels a powder bed. The needed powder for each layer is stored and provided by a reservoir near the manufacturing space. Layers reach a thickness between 20 – 100 μm depending on the requirements [6]. The powder is melted with the help of a galvanometer scanner, which steers the used laser beam in a pre-defined scan strategy over the powder bed. Wavelengths for the used lasers are most common in the 1060 – 1080 nm range and come in the form of single fibre lasers operated in a continuous wave mode [7]. During the process inert gas is pumped in the manufacturing area to shield the powder bed from oxidation and to remove small debris flowing through the air.

Commercial LPBF machines can manufacture tiny complicated components with high precision, but this takes a long time. In addition, the powder bed is not fully utilised during the process and has to be removed, which is time-consuming and poses potential risks for health and environment. If hollow spaces are present in the manufactured part, these could be filled with powder, which is unwanted. Left over powder can be reused depending on the powder investigated by about 30% [8].

### 2.2 Wire Arc Additive Manufacturing Process

Another used MAM process is the Wire Arc Additive Manufacturing or short WAAM. It is a direct energy deposition process, in which a metal wire is molten with the heat from an electric arc. It relies on the conventional gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) or plasma arc welding automated with the help of robots or Computerized Numerical Control (CNC) router tables. A welding torch is travelling in a pre-planned path and deposits the material weld by weld and layer by layer. Gas Metal-Wire and Arc Additive Manufacturing can achieve large deposition rates from 15 – 160 g/min, which makes it ideal to manufacture simple or large-scale parts in short time periods [9].

The GM-WAAM process is easy to setup and basic equipment is cheap to buy in comparison to industrial LPBF printers, but the correlation between the welds and the movement can be complicated, since there is a little bit of randomness in the arcs form which melts the material and the deposition is therefore not always uniform on the surface. During the process, there could be accumulation of material on some areas of the part. This changes the contact tube to work distance (CTWD), which is a crucial parameter in WAAM to get the deposition of material and shape of the part right [10]. Every material that is weldable can be manufactured with WAAM. Some materials like magnesium or titanium can be much safer to handle in wire form than in the form of small pyrophoric particles as is the case in some LPBF powders [11].

## 3 Life Cycle Assessment According to ISO 14040ff

Following the literature research on sustainability assessments that have already been carried out within the LPBF process as described by Wurst et al. (2022) [2], a large number of LCAs have already been conducted since 2015 (cf. e.g. Peng et al. (2020) [12]). Additionally, the focus in current publications, such as the case study presented by Priarone et al. (2020), is on the sole consideration of the process chain of the WAAM process, without any comparison to other additive or conventional manufacturing processes [13]. Adapted from this and according to the ISO 14040ff. Series of standards, the Life Cycle Assessment (LCA) is divided into the four phases of "Goal and Scope", "Life Cycle Inventory", "Life Cycle Impact Assessment" and "Interpretation of Results", which are explained and applied in the following by means of the specific example of the comparative case study [14, 15].

### 3.1 Goal and Scope

#### 3.1.1 Reasoned Demonstrator Selection

In this case study, a demonstrator made of aluminium was adopted for both manufacturing processes as a hollow sphere on a platform (cf. Fig. 1). This demonstrator was chosen because of its particular challenges for both used MAM techniques.

The demonstrator should be relatively easy to manufacture with a commercially available alloy but nonetheless demonstrate the particular benefits of MAM and help to compare LPBF to WAAM. In the pre-process stage, CAD model of the demonstrator was created and then for the LPBF sliced and put into a Simulation to calculate the data needed for the LCA before the in-process within the manufacturing phase. For the WAAM pre-process, the planned dimensions were taken into consideration while programming a predetermined welding route into a six-axis industrial robot which moves the welding torch. Firstly, there is the cubic section from the substrate to the sphere, which increases the height of the print job and therefore the total build time for LPBF, while WAAM has the problem to manufacture it in a near net shape form. Secondly, the connection between the cubic and the following sphere section poses a challenge in binding both parts. For the sphere itself the LPBF technique needs support structures to manufacture a hollow part correctly, and the WAAM needs a tilting mechanism and a rotating axis to weld the layers. Closing the sphere completely is the last challenge, as here the LPBF part has still support structures and powder inside the sphere and the WAAM sphere becomes problems to close the sphere when there is too much shielding gas pressure. In the post-processing stage, the LPBF demonstrator has to be cleaned and the WAAM demonstrator to be cooled down to room temperature and was removed from the fixture on top of the six-axis robot. Further cleaning was not necessary.

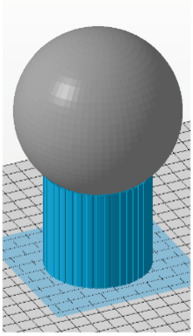


**Fig. 1** Model of the hollow sphere incl. required support structures for the LPBF process

### 3.1.2 Manufacturing of the Demonstrator

Within the software for the LPBF process a detailed simulation of the manufacturing process can predict information concerning e.g. the needed time and amount of monomaterial, and therefore for the following LCA. The outstanding data needed for the LCA was calculated, based on manufacturing parameters and machine properties by formulated phase- and processspecific functions.

For the WAAM process, the planned demonstrator had to be transferred from a CAD model into a path planning for the six-axis robot holding the substrate plate. The width of each weld and the height of each layer was taken into consideration and the welding parameters were changed accordingly to get a near net shape geometry close to the CAD model. The sphere was more difficult, since all the six-axes were needed to get a good welding result and the path planning for the sphere was done with a changing radius as base for the programmed algorithm. The welding torch is circling the predefined radii with a varying angle of attack (45° to 125° from bottom to the top), in contrast to the orthogonal angle of attack. Since the exact position and dimensions of each weld and therefore layer is unknown, it is difficult to predict exactly where the robot needs to be for the next layer, so a correction factor was empirically determined. To get even layers, the start point of each weld was changed by 5° compared to the previous and for correcting the CTWD in process two external switches for changing the distance by ±0,5 mm are made. Before closing the sphere completely, the manufacturing was stopped to be able to examine the interior and not endanger the torch.

With the time spent manufacturing, the data needed for the LCA was calculated from the flow of shielding gas, voltage protocols of the welding machine and properties of the six-axis robot, welding equipment and the cooling ventilators. The wire spool was weighted before and after the building process as well as the substrate and the finished demonstrator. For welding, a Fronius TransPuls Synergic 4000 CMT R was used in CMT mode, the 1,2 mm wire was delivered via the accompanying VR 7000 CMT and the process was controlled with the RCU 5000i remote. The demonstrator was moved under the torch with a KR125/1 from KUKA Systems GmbH. The path planning was done in the KUKA KRL language.

### 3.2 Life Cycle Inventory

According to the previously defined requirements for this case study, comparable "cradle-to-gate" process chains are set up for both manufactured products to be able to quantify an evaluation of the two products that is as holistic as possible. Depending on the associated investigation of the process phases from resource extraction to the end of the production phase, process steps of these phases are defined in each case and linked with each other as transitions using Petri nets [16]. In Fig. 2, the phases considered in this context and the process steps linked within them are listed for the WAAM and LPBF processes.

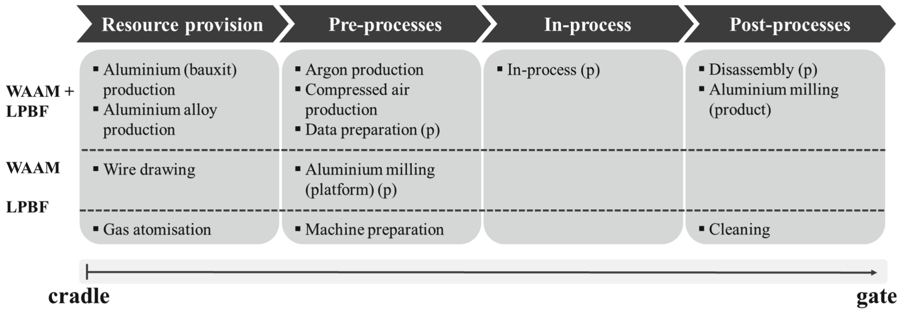



**Fig. 2.** Considered phases and process steps of the WAAM as well as LPBF method

Within the phases of the Life Cycle Inventory (LCI), process steps and therefore related transitions are created within these identified phases [16]. Each transition contains inputs and outputs, which are linked to connectors. The resulting network is supplemented with both primary collected data from the production phase and secondary supplemented data from the ecoinvent database. This secondary data relates, for example, to resource provision, including cross-process aluminum extraction and wire or powder production. Figure 2 shows a concrete listing of the transitions investigated, and the primary data collected are indicated by a (p). In addition, a listing of these concrete primary data collected for both manufacturing processes is summarized in Table 1. For increasing the generalizability of this model, the primary collected parameters are linked to Umberto LCA + via LiveLinks through a data collection sheet, allowing a process-oriented as well as demonstrator-specific calculation of the life cycle inventory data using functions integrated in the material flow network.

In this context, it is important to mention that the demonstrator to be manufactured by means of the LPBF method exists only as a digital model. All primary data originate from a simulation by the EOS software for specifying the efforts of the component manufacturing by using the EOSINT M280. Furthermore, the high degree of necessary support structures must be restricted through the fact that the required base is only necessary for the LPBF process and that a high degree of primary powder could be saved by manufacturing only the hollow sphere.

**Table 1.** Primary collected data

| Scenario | Phase | Primary data | Quantity |
|---|---|---|---|
| WAAM | Data preparation (p) | Duration of programming | 100 h |
| | Aluminium milling (platform preparation) (p) | Duration of the milling process | 0,33 h |
| | | Mass of the substrate plate | 0,269 kg |
| | | Amount of metallic waste | 0,006 kg |
| | | Consumption quantity of lubricants | 0,01 ml |
| | Machine preparation (p) | Time required for system preparation | 1,075 h |
| | | Volume of propane gas (preheating of the platform) | 0,0167 l |
| | In-process (p) | Application rate | 85.621 $mm^3/h$ |
| | | Cooling unit capacity | 0,24 kW |
| | | Duration of material application | 1,7 h |
| | | Mass of welding wire | 0,393 kg |
| | | Material preservation | 98,7% |
| | | Performance of the whole system | 1,021 kW |
| | | Volume of inert gas (argon) | 1.635 l |
| | | Volume of final product | 135.010 $mm^3$ |
| | Disassembly (p) | Duration of disassembly | 1,375 h |
| LPBF | In-process (p) | Amount of primary powder | 6.693.750 $mm^3$ |
| | | Amount of secondary powder | 2.868.750 $mm^3$ |
| | | Building rate | 0,05 $mm^3/h$ |
| | | Duration of the material application | 96,3875 h |
| | | Performance of the system (EOSINT M280) | 3,2 kW |
| | | Volume of inert gas (argon) | 1.311,438 l |
| | | Volume of product including support structures | 439.450 $mm^3$ |

### 3.3 Life Cycle Impact Assessment

For comparing the two different manufacturing processes based on their environmental impacts, digital models of the process chains are created in "Umberto LCA +" for both the LPBF process and the WAAM process. For this study, Umberto LCA + version 10.0.3 and related data sets from the ecoinvent v3.7.1 database was used.

The two process chains were each divided into four life cycle sub-phases in order to simplify the identification of hotspots in the context of the calculation and subsequent analysis of the Life Cycle Impact Assessment (LCIA).

In each of these four phases, different transitions with inputs, outputs as well as connection points are placed and linked to form a logical network according to the Petri net method. To use the individual connected transitions as a generalized system, functions for product-, process- and material-specific inputs and outputs are formulated within these transitions. Each of these functions can be influenced by parameters, which are directly linked to the data collection sheets of the investigated production phase by using LiveLinks, allowing a direct data exchange or recalculation of the function results within the transitions [16]. In order to be able to present the results of the LCIA of both additive manufacturing processes in comparison among one another, 18 impact categories were calculated applying the "ReCiPe (H)" method throughout both calculations [17]. In Table 2, the ecological impact for the WAAM and the LPBF process is shown depending on the examined phase in the product life cycle.

## 4 Interpretation

During the phaseoriented analysis of the LCIA results, hotspots can be identified in the life cycle phases of the pre-process for the WAAM method as well as resource provision and in-process for the LPBF method (cf. Table 2). These hotspots, though, are not overarching for all calculated LCIA categories, but refer to individual impact categories in each case. In this study, a hotspot is defined as a significant impact of an LCIA category that exceeds the value of the compared process by at least double while also indicating a significant impact in the overall LCIA-category comparison.

### 4.1 Hotspots WAAM

According this definition, for the demonstrator produced by the WAAM process, two primary hotspots can be identified within the pre-process phase. Firstly, inside the "global Warming Potential" (GWP100) and secondly, inside the "Fossil Depletion" (FDP) (cf. Table 2). In relation to the calculated individual transitions or process steps, these maxima can be analyzed to identify both influential transitions and specific material flows. For the category of GWP100, the process steps of "aluminium milling" (0.62 kg CO2-Eq) and "argon production" (0.72 kg CO2-Eq) have the 10% share of the highest impact [16]. Within these process steps, it is also possible to formulate a statement regarding the material flow with the highest impact. In the milling process, the machining of aluminum alloys creates an impact of 0.48 kg CO2-Eq and thus accounts for 77.42% of the total impact of this process step. In relation to the energy-intensive argon production, even 82.89% (0.63 kg CO2-Eq) of the total impact is caused by one material flow, in this case "carbon dioxide, fossil", which in turn can be explained by the high electricity consumption required.

**Table 2.** LCIA-results of the investigated WAAM and the LPBF process

| | | | Resource provision | | Pre-processes | | | In-process | | Post-processes | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Potentials | | | WAAM | LPBF | WAAM (process/ component) | | LPBF | WAAM | LPBF | WAAM | LPBF |
| **ALOP** | agricultural land occupation | **m2a** | 3,34E-03 | 1,52E+00 | 3,00E-02 | 2,00E-02 | 3,00E-02 | 3,17E-04 | 5,00E-02 | 5,28E-03 | 7,00E-02 |
| **FETPinf** | freshwater ecotoxicity | **kg 1,4-DCB-Eq** | 2,25E-03 | 9,70E-01 | 4,00E-02 | 7,00E-02 | 2,20E-01 | 6,20E-04 | 6,00E-02 | 4,00E-03 | 1,20E-01 |
| **MDP** | metal depletion | **kg Fe-Eq** | 8,71E-03 | 4,33E+00 | 4,00E-02 | 2,00E-02 | 6,40E-01 | 1,57E-03 | 9,00E-02 | 2,65E-03 | 4,00E-02 |
| **ULOP** | urban land occupation | **m2a** | 4,49E-04 | 2,10E-01 | 4,00E-02 | 1,00E-02 | 1,20E-01 | 6,27E-04 | 2,00E-02 | 4,19E-03 | 2,00E-02 |
| **TAP100** | terrestial acidification | **kg SO2-Eq** | 1,42E-04 | 7,00E-02 | 4,04E-03 | 3,46E-03 | 2,98E-03 | 2,45E-04 | 2,00E-02 | 1,83E-04 | 7,61E-03 |
| **NLTP** | nature land transformation | **m2** | 5,97E-06 | 1,92E-03 | 1,42E-04 | 1,17E-04 | 1,86E-04 | 6,30E-05 | 4,64E-03 | 3,22E-05 | 2,86E-04 |
| **TETPinf** | terrestial ecotoxicity | **kg NMVOC** | 7,91E-05 | 1,00E-02 | 5,44E-05 | 1,41E-04 | 1,15E-04 | 3,40E-06 | 2,82E-04 | 8,62E-05 | 2,47E-03 |
| **POFP** | photochemical oxidant formation | **kg NMVOC** | 9,07E-05 | 4,00E-02 | 2,74E-03 | 2,32E-03 | 2,29E-03 | 2,17E-04 | 2,00E-02 | 1,64E-04 | 6,20E-03 |
| **HTPinf** | human toxicity | **kg 1,4-DCB-Eq** | 2,00E-02 | **8,04E+00** | 4,20E-01 | 3,00E-01 | 8,30E-01 | 6,24E-03 | 7,40E-01 | 5,00E-02 | 1,75E+00 |
| **IRP_HE** | ionising radiation | **kg U235-Eq** | 3,55E-03 | 1,73E+00 | 1,60E-01 | 2,00E-02 | 8,00E-02 | 1,00E-02 | 9,00E-01 | 2,26E-03 | 2,10E-01 |
| **WDP** | water depletion | **m3** | 4,00E-04 | 1,50E-01 | 4,71E-03 | 6,80E-03 | 4,52E-03 | 2,78E-04 | 5,97E-03 | 4,33E-03 | 1,30E-01 |
| **ODPinf** | ozone depletion | **kg CFC-11-Eq** | 4,94E-09 | 2,18E-06 | 3,02E-08 | 2,84E-08 | 6,77E-08 | 3,16E-08 | 2,24E-06 | 4,01E-09 | 1,16E-07 |
| **METPinf** | marine ecotoxicity | **kg 1,4-DCB-Eq** | 2,00E-03 | 8,60E-01 | 3,00E-02 | 6,00E-02 | 1,90E-01 | 5,10E-04 | 5,00E-02 | 3,65E-03 | 1,10E-01 |
| **PMFP** | particulate matter formation | **kg PM10-Eq** | 5,71E-05 | 3,00E-02 | 2,63E-03 | 1,68E-03 | 1,80E-03 | 7,97E-05 | 8,27E-03 | 1,33E-04 | 5,84E-03 |
| **FDP** | fossil depletion | **kg oil-Eq** | 5,80E-03 | 2,41E+00 | **2,90E-01** | **1,60E-01** | 2,00E-01 | 7,00E-02 | 4,70E+00 | 1,00E-02 | 5,40E-01 |
| **MEP** | marine eutrophication | **kg N-Eq** | 3,91E-05 | 2,00E-02 | 1,03E-03 | 8,72E-04 | 8,06E-04 | 5,80E-05 | 5,04E-03 | 1,34E-04 | 4,44E-03 |
| **GWP100** | global warming | **kg CO2-Eq** | 3,00E-02 | **1,31E+01** | **1,02E+00** | **7,00E-01** | 7,30E-01 | 1,90E-01 | **2,00E+01** | 6,00E-02 | 4,66E+00 |
| **FEP** | freshwater eutrophication | **kg P-Eq** | 1,20E-05 | 4,40E-03 | 5,41E-04 | 2,36E-04 | 5,62E-04 | 4,03E-06 | 6,92E-04 | 1,78E-05 | 1,01E-03 |

## 4.2 Hotspots LPBF

Within the analysis of the LPBF method, hotspots can also be identified within the "cradle-to-gate" consideration (cf. Sect. 4.1). In contrast to the WAAM method, these hotspots can be detected in the "resource provision" phase as well as in the "in-process" phase (cf. Table 2, 11). For both of these phases, the LCIA category of "global warming potential" constitutes a significant share of the total impact. In addition, a hotspot within the category "human toxicity potential" can be identified in the context of the "in-process" (cf. Table 2). The resource provision shows an increased impact of 5.3 kg CO2-Eq in the process step of aluminum preparation out of scrap in the GWP100 category. With a fourfold of this amount, the GWP100 value within the in-process is at 13.1 kg CO2-Eq caused by the process step of energy provision. Both of these are caused by the material flow "Carbon dioxide, fossil", which forms 58.30% (3.09 kg CO2-Eq) in the aluminum preparation and 93.05% (12.19 kg CO2-Eq) in the energy supply of the respective total GWP100 value.

In addition, a further hotspot in the LCIA category "human toxicity potential" appears in the resource provision phase, which can be explained by the process step "aluminum alloy production".

During this process step, a significant amount of the HTPinf category is generated by the copper required for the aluminum production. By using it as cathode within this process step, this material flow generates an impact of 0.55 kg 1,4-DCB-Eq and thus a share of 25% of the total impact of the aluminum alloy production (2.20 kg 1,4-DCB-Eq).

## 5 Conclusion and Outlook

In this paper, aspects of a case study comparing two metallic additive manufacturing processes was presented. Based on the calculations of life cycle assessments according the 14040 ff. Series of standards, it is possible to model material flows as a material flow network along the investigated "cradle-to-gate" process of the demonstrators' product life cycle and summarize these flows in life cycle inventories. A subsequent calculation of a life cycle impact assessment by the ReCiPe(H) method by using the Umberto LCA + software furthermore enables the identification of concrete hotspots along the entire process chains.

These hotspots provide the basis for various conclusions:

- During the hotspot analysis an obvious one was the large amount of time and human resources needed pre- and in-process. This factor could decrease in the future with better automation technology and control technology to provide a closed loop CTWD monitoring in-process [18].
- Excluding the resulting component quality, the calculated ecological impact of the WAAM process for the investigated demonstrator is lower than for the LPBF process. In addition, the costs, especially the high personnel costs within the pre-process (WAAM), are not considered in the current evaluation as well. In order to be able to make holistic statements regarding the sustainability of both processes in comparison, further case studies must be carried out, data collected and calculations extended to other dimensions [19].

**Acknowledgement.** This research has been funded by the Ministry for Science and Culture of Lower Saxony (MWK) – School for Additive Manufacturing SAM. And we like to thank the Fronius International GmbH for providing the GMAW source.

## References

1. Tofail, S.A., Koumoulos, E.P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., Charitidis, C.: Mater. Today **21**, 22–37 (2018)
2. Wurst, J., Mozgova, I., Lachmayer, R.: Sustainability assessment of products manufactured by the laser powder bed fusion (LPBF) process. In Procedia CIRP **105**, 243–248 (2022). https://doi.org/10.1016/j.procir.2022.02.040
3. ISO, ASTM: Additive Manufacturing—Design—Requirements, Guidelines and Recom-Mendations (ISO/ASTM 52910:2018) 25.030
4. Vafadar, A., Guzzomi, F., Rassau, A., Hayward, K.: Advances in metal additive manufacturing: a review of common processes, industrial applications, and current challenges. Appl. Sci. **11** (2021). https://doi.org/10.3390/app11031213

5. Gibson, I., Rosen, D., Stucker, B., Khorasani, M.: Additive Manufacturing Technologies. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-56127-7
6. Lachmayer, R., Lippert, R.B.: Entwicklungsmethodik für die Additive Fertigung. Springer, Berlin (2020). https://doi.org/10.1007/978-3-662-59789-7
7. Herzog, D., Seyda, V., Wycisk, E., Emmelmann, C.: Additive manufacturing of metals. Acta Mater. **117** (2016). https://doi.org/10.1016/j.actamat.2016.07.019
8. Powell, D., Rennie, A.E.W., Geekie, L., Burns, N.: Understanding powder degradation in metal additive manufacturing to allow the upcycling of recycled powders. J. Clean. Prod. **268** (2020). https://doi.org/10.1016/j.jclepro.2020.122077
9. Rodrigues, T.A., Duarte, V., Miranda, R.M., Santos, T.G., Oliveira, J.P.: 2019): Current status and perspectives on wire and arc additive manufacturing (WAAM. Materials **12**, 1121 (2019). https://doi.org/10.3390/ma12071121
10. Xiong, J., Zhang, G.: Adaptive Control of deposited height in GMAW-based layer additive manufacturing. J. Mater. Process. Technol. **214**, 962–968 (2014). https://doi.org/10.1016/j.jmatprotec.2013.11.014
11. Chen, R., et al.: Exposure, assessment and health hazards of particulate matter in mental additive manufacturing: A review. Chemosphere **259** (2020). https://doi.org/10.1016/j.chemosphere.2020.127452
12. Peng, T., Wang, Y., Zhu, Y.: Life cycle assessment of selective-laser-melting-produced hydraulic valve body with integrated design and manufacturing optimization: A cradle-to-gate study. Addit. Manuf. (2020)
13. Priarone, P.C., Pagone, E., Martina, F., Catalano, A.R., Settineri, L.: Multi-criteria environmental and economic impact assessment of wire arc additive manufacturing. CIRP Ann. **69**(1), 37–40 (2020). https://doi.org/10.1016/j.cirp.2020.04.010
14. Frischknecht, R.: Lehrbuch der Ökobilanzierung. Springer, Berlin (2020). https://doi.org/10.1007/978-3-662-54763-2
15. International Standard Organization: Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040:2006 + Amd 1:2020). Deutsches Institut für Normung e.V. Beuth Verlag GmbH, Berlin (2021)
16. Wurst, J., Steinhoff, T.: Petri net in the "cradle-to-gate" system for the Wire Arc additive manufacturing and the laser powder bed fusion process (Umberto LCA+). Institutional Repository of Leibniz Universität Hannover (2022)
17. Lammerant, J.: Aseesment of Biodiversity Measurement Approaches for Business and Financial Institutions. European Comission B@B (2019)
18. Hölscher, L.V., Hassel, T., Maier, H.J.: Detection of the contact tube to working distance in wire and arc additive manufacturing. The International Journal of Advanced Manufacturing Technology **120**(1–2), 989–999 (2022). https://doi.org/10.1007/s00170-022-08805-0
19. 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

# Evolving Markets in the Circular Economy: A Network Analysis of Exemplary Company Cases

Katie Louise Leggett[1(✉)], Juri Mykkänen[1,2,5], Petteri Repo[3,4,5], and Minna Lammi[1,3]

[1] Anglia Ruskin University, Cambridge CB1 1PT, UK
Katie-louise.leggett@aru.ac.uk
[2] University of Helsinki, 00014 Helsinki, Finland
[3] Centre for Consumer Society Research, University of Helsinki, 00014 Helsinki, Finland
[4] Helsinki Institute of Sustainability Science, 00014 Helsinki, Finland
[5] Helsinki Institute of Urban and Regional Studies, 00014 Helsinki, Finland

**Abstract.** The circular economy is a production and consumption model which seeks to use materials and products for as long as possible, whilst keeping waste to a minimum. This study aims to understand the characteristics of the emerging Finnish circular economy marketplace. A network analysis was used on a sample of 41 exemplary cases in Finland, taken from the circular economy business case collection published by the Finnish Innovation Fund Sitra. The coding process led to the identification of 79 nodes and 577 connections between them which are depicted in this study as a network visualisation. Similarities were found between organisation's age and size, with large older organisations and established small and medium sized organisations excelling in optimising product life cycles and reducing overconsumption and new micro sized organisations thriving in managing resource flow and retrieving and recycling materials to put back into the system. Thus, organisations seeking to expand into or transform their operations in line with the circular economy may find the optimal circular economy activity dependent on their size, with large organisations shown to be thriving in repair and redesign activities, small and medium sized organisations in rent and reuse activities and micro sized organisations with retrieve and recycling activities.

**Keywords:** Circular economy · Business models · Network analysis · Finland

## 1 Introduction

The circular economy (CE) has been a feasible option to make businesses more sustainable. The new economic model builds on multiple solutions based on using natural resources as effectively as possible. However, for any business to start a CE type operation or to transform its processes into circular, it needs a viable market for its products or services. Functioning CE markets, on the other hand, require at least moderately widely distributed knowledge of available technologies, availability of new raw materials, change in consumers' needs and practices, or regulatory frameworks that either


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 98–109, 2023.
https://doi.org/10.1007/978-981-19-9205-6_10

encourage new investments or make reduction of waste mandatory. This can be summarised by looking at some fundamental ways companies can use the opportunities presented to them by the unsettling market components. Here we look at how different CE practices connect with the CE business archetypes to create a necessary background for an empirical assessment of the evolving CE market in Finland. Our example country, Finland, has been ranked as one of the leading countries in circular business actions along with France [1].

Although markets based on the principles of the CE have been in the making for a long time, we still have relatively scant knowledge of what are the characteristics of such markets. What fields of industry are most developed in the CE and what are the typical products that comply with the CE requirements? How are the businesses organised and to what concrete ways do they resort in order to engage in the CE? Essentially, this boils down to various business models that utilise circular methods, such as recycling waste materials or repairing worn parts and returning them into use. To answer these questions, we will focus on a selection of 41 Finnish companies that are judged to be exemplary operators in CE markets.

The methodology used in this study is quite unique in the field of research that studies evolving CE markets. We employ a network analysis to understand how the CE business archetypes are adopted in forward-looking CE business cases. By identifying clusters of company attributes, industry areas and CE practices, we can identify core business models and reconstruct an evolving CE market structure.

## 2 How Do Companies Engage in the Circular Economy?

A number of business models have been demonstrated to help companies in their efforts to become circular and it has become an established way to review these models as archetypes [2, 3]. In this paper we rely on the nine archetypes reported by Haffmans et al. (2018) and Bakker et al. (2020) because they cover the field comprehensively and connect well to the strategic activities of a wide range of companies. These are the flow management model, the reversed logistics model, the separation and sorting model, the recycling model, the classic long-life model, the hybrid model, the gap exploiter model, the access model, and the performance model [4, 5].

In looking at how exactly the companies adjust their activities to the requirements of the CE, we are advised to break down the business models into their constitutive circular parts, namely the well-known seven R's, Redesign, Reduce, Reuse, Renew, Repair, Recycle, and Retrieve [6]. The R's entail the selection of basic circular business activities or the manner of closing or extending the loop of the material flow of production.

It is not altogether clear if pay-per-use type of business or traditional rentals should be included in the circular business practices alongside the seven R's as renting is a very old practice, indeed. However, renting, sharing and other types of temporary access to a product or service against payment involve ways of reducing material consumption, enhancing efficient use of products and encourage manufacturers to build longer lasting products, which can then be reused in some form at the end of their life cycle [7, 8]; it is also the fundamental principle of the access model of the circular business archetypes [5]. These will have positive effects on ecological sustainability, which is at the heart of CE (for a sceptical view, see Tukker 2004 [9]). Thus, we include Rent as the eighth R.

How business models and CE practices support each other can be seen in Table 1.

These nine circular business archetypes, with their corresponding R's, provide a suggestive framework for businesses to implement CE principles. However, the boundaries between these frameworks are fluid and there can be overlapping practices. As can be seen in the table above, many of these circular business archetypes share similar circular practices. Further, it is useful to recognise the strategic difference between closing the loop through retrieval and recycling and slowing it down for instance through an extension of product lifespan [10].

Fundamentally, when it comes to designing for circularity there are many key considerations and practical issues, such as durability, standardisation and compatibility, ease of maintenance and repair, adaptability and upgradability, and disassembly and reassembly, as well as emotional properties, such as attachment and trust [5]. Answering all these different requirements constitutes a functioning CE market, the value of which can be communicated to the consumers to aid with their decision-making process. As Azad et al. (2013) suggest, for a CE market to get established, there must be unity across the whole process, from the conception of the market offerings and product design down to the marketing and after-sales [11].

Although there exist several business models for companies to adopt CE practices, empirical evidence tells that overall, only some of them seem to be in wider use. In Europe, for example, Bassi and Dias (2019) found that only a minor portion of companies had resorted to any kind of CE business model. Often the reason for the slow or limited adoption of CE seems to lie in the shortage of resources, but they also found that there is sizable variation between countries [12]. Further evidence suggests that CE businesses focus on a narrow selection of CE methods. For example, in their world-wide survey of different organisations, Barreiro-Gen and Lozano (2020) observed that most organisations (including business organisations) relied on recycling and waste reduction in their CE profiles and much less on repairing or remanufacturing [13]. A recent study of 11,000 companies points at a similar pattern: waste reduction and process redesign to minimise material use are prioritised by most companies [14]. However, there is also evidence that points at a more positive development. According to a study by Garcés-Ayerbe et al. (2019), we can identify a pattern of gradual expansion of CE practices on a company level [15]. For example, a company may at first transform a small part of its operation, say, water management, to become circular, and after that expand circularity to include an individual product line before turning most or all operations circular. Against this background, it would be interesting to take a closer look at a selection of leading CE companies and how the CE market is developing. Before doing that, we introduce our empirical material and methodology.

## 3 Data and Methodology

To recognise empirical applications of forward-looking business archetypes, we examine a collection of 41 vanguard circular economy business cases collected and published by the Finnish Innovation Fund Sitra [16]. Sitra is a public foundation established in 1967 and operates under the Finnish Parliament to promote the stable development of Finland. Sitra has been actively promoting the CE for a long time and published the world's first

**Table 1.** Circular business archetypes and corresponding R's

| Circular business archetype | Corresponding R's |
|---|---|
| The Flow Management Model: Optimising and reducing the reliance on energy and resources. Technology can contribute here, sometimes replacing flow systems into immaterial systems | Reduce (reducing materials and energy use in the processes) and Redesign (of the systems to utilise technology) |
| The Reversed Logistics Model: Product is returned to the original sources. It can be used in cases of repair, maintenance, return upon failure and after the product is no longer required | Reuse (product may be put back into the system second-hand), Repair (repair of the product), Recycle (recycled materials may be used), Renew (full restoration of the product) & Retrieve (products may be reclaim) |
| The Separation and Sorting Model: Collecting waste to be seperated back into their raw materials and sorted for further use | Recycle (materials are recycled after separation and sorting) & Retrieve (materials are separated and sorted which may have been missed from other mainstream processes) |
| The Recycling Model: Organisation of the right processes for recycling and retrieving renewable materials from the flow system by either purification or composting or into biofuel, or a last option of thermal recycling or burning | Recycle (materials are recycled which have been contaminated and cannot go straight back into the circulatory system without purification first) & Retrieve (materials are retrieved which have been contaminated) |
| The classic long-life model: Proposes that high quality products are produced to ensure a long lifespan, the high price point is the main source of income, after-sales support is crucial to the high-quality consumer perception, service and repair are also integral | Reduce (longer lifespan)<br>& Repair (after sales support to ensure longer lifespan) |
| The hybrid model: Revolves around the sales of products and parts which only function when used with a long-lasting product, both products cannot function on their own | Repair (the part allows for the repair of the long-lasting product) & Renew (the new part may renew the product to its original performance or aesthetic) |
| The gap exploiter model: Finds value gaps in the existing system, here a third party between the original provider and the user repairs, sells second-hand or converts | Redesign (alterations to the original), Reuse (second-hand), Repair (repair of the product), Recycle (recycled materials may be used), Renew (full restoration of the product) & Retrieve (products may be reclaimed from waste and rejuvenated) |
| The access model: Provides consumers access to a product whilst retaining business ownership | Rent (the products are rented to the consumer), Reduce (once products are returned, they can be rented to subsequent users) & Reuse (platform businesses allowing unwanted products to be sold or exchanged) |

(*continued*)

**Table 1.** (*continued*)

| Circular business archetype | Corresponding R's |
|---|---|
| The performance model: The product is retained by the service provider; users are only interested in the service performance rather than the products used | Reduce (products are not purchased by many individuals but rather less are used by businesses) & Reuse (one product used to satisfy multiple customers) |

national roadmap to CE in 2016. It was honoured as the leading public-sector CE actor by the World Economic Forum in 2018. The list of the CE cases is intended to stimulate Finnish companies to embrace the CE in a profitable way. It should be noted that the selected companies do not represent all Finnish companies that have elements of CE in their operations but are rather a selection of companies that are particularly interesting in their take on CE and considered exemplary cases.

The 41 cases were encoded by two of the authors and reviewed by the other two to cover key characteristics recognized in studies on CE. Disagreements in coding were minimal and were resolved by reviewing the particular cases by all authors jointly and then negotiated to achieve consensus.

In previous studies on companies' involvement in the CE, typical variables have included the company's age, its size and the share of CE in its turnover. For example, in their well-known study, Urbinati et al. (2017) found that older and larger companies were usually among the most successful in implementing CE practices in their operation. They also noted that very young companies without history in linear production could succeed well [17]. These findings were corroborated by Bassi and Dias (2019) [12]. Looking at other similar studies, the results seem somewhat mixed. It is not always clear that start-ups or other micro companies would be spearheading in CE [14]. In fact, Garcés-Ayerbe (2019) observed that midsized companies have the best chances in transforming their operations according to CE requirements [15]. Based on these studies, it would seem logical that old and established companies with large assets and investment capital were in a better position to alter production to meet CE criteria and increase the share of CE in the turnover. Likewise, newly founded businesses may jump directly into the emerging CE market without the burden of having the other foot in the linear economy. In that case, it follows that the share of CE in the turnover of these companies is naturally high.

To better understand how companies engage in CE practices, we need to focus on these practices in more detail. As this study is based on the idea of CE business archetypes and their various use of the circularity R's that describe the different ways businesses can become circular, we naturally included the R's (see table 1) in our list of variables. As said, we added one more, namely 'rent' as the traditional seven seem to exclude renting and other pay-per-use activities. In terms of the type of CE innovation on which the companies' business is focused, Katz-Gerro and Sintas (2018) found that at least in the EU-28 countries most CE innovations are located in industrial manufacturing and natural resource management. According to this study, the service sector is by far the least active in using CE innovations [14]. Following their example, we used three categories denoting the type of CE innovation: product, service, and process. In addition, we looked at the companies' self-reported field of industry [18] and what the companies produce as important factors in understanding the structure of CE-related business. The variables are listed in Table 2 below.

**Table 2.** Variables and variable categories

| Variables | Variable Categories |
|---|---|
| Age | Old = founded before 1994; Established (est) = founded between 1995 and 2010; New = founded after 2010 |
| Size | Micro (MSE) = turnover $<$ 1 me or staff size $\leq$ 10; Small and medium sized (SME) = turnover 1–50 me or staff size 10–250; Large (LE) = turnover $>$ 50 me or staff size $>$ 250 |
| CE Share of Turnover | Low = 0–33%; Medium = 34–66%; High = 67–100% |
| Type of CE Activity | Redesign; Reduce; Reuse; Renew; Repair; Recycle; Retrieve; Rent |
| Type of CE Innovation | Product; Service; Process |
| Field of Industry | Several codes based on information given by companies (e.g., plastics, retailing, textiles, transportation, waste and recycling) |
| Product or Service | Several codes based on information given by companies (e.g., construction materials, biofuels, biogas, proteins, cardboard) |

The encoding procedure led to 79 codes and 1,024 co-occurrences of codes, contributing to a network with 79 nodes and 577 edges. We applied the Gephi network software [19] to conduct data analysis and visualisation of the codes. Key analyses concern calculation of connections (degrees) and clustering (modularity) of codes. The data visualisation of the network relies on the ForceAtlas2 layout, which simulates a physical system in which nodes push away from each other while edges draw them closer. It is force-directed, and the placement of nodes depends on that of other nodes. ForceAtlas2 can be described as a generic way to perform network visualisation as it draws on features from other established network models [20].

## 4 Results

The network visualisation (Fig. 1) builds on the connections of the coded company cases. As results are presented in the format of a network, they transcend categorizations and connect coded characteristics across cases and collections of similar cases. For instance, 'textiles' is a central code and connects to 'High CE' (7), which represents a high share of circular economy in the observed product, 'MSE' (micro-sized enterprises, 5), 'retrieve' (5), 'clothing' (5) and 'SME' (small and medium-sized enterprises, 3). Accordingly, the connecting characteristics of textiles show why it is meaningful to observe the CE case collection as a connected network of characteristics rather than in a categorical way.

The sizes of the nodes represent how much the codes are connected to other codes. For instance, the node 'High CE', which represents a high share of circularity of the

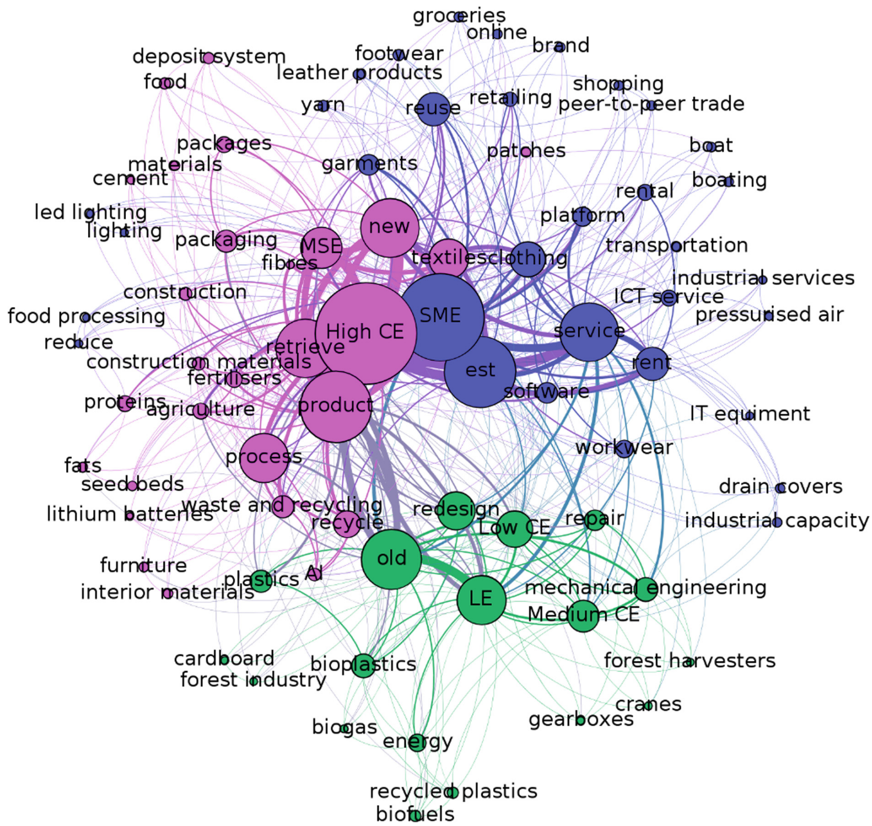



**Fig. 1.** Coded circular economy networks

innovation in question, is large in size because it has many connections in its originating purple cluster's 'product' (16), 'retrieve' (14) and 'new' (new companies, 13), while also connecting to the blue cluster's 'SME' (17), 'est' (established companies, 10) and 'service' (10) as well as the green cluster's 'old' (old company, 8), LE (large enterprise, 5) and 'redesign' (2). From this we can deduce that a high share of circularity takes place in activities of new companies' product innovations relating to retrieval of materials, while established SME's focus more on services with a high share of circularity and that old and large enterprises' activities in redesign achieve a high share of circularity.

Clusters according to the type of CE activity were identified with a modularity algorithm [21, 22]. Connections between nodes within these clusters are denser than with nodes in other clusters. This procedure led to the identification of three clusters of the type of CE activity: 1) retrieval of materials, 2) services, and 3) mechanical engineering.

The cluster on retrieval of materials is coloured in purple and focuses highly on CE, connects to agriculture as well as waste and recycling, and involves micro sized enterprises (MSE). The second service cluster (in blue) revolves around rentals, reuse, clothing and established small and medium-sized companies (SME). The third cluster of mechanical engineering (in green) involves old and large enterprises (LE) with a low or medium share of CE and focuses on redesign and repair mostly in machinery and plastic production.

Referring to Table 1, which showed the nine circular business archetypes models [4, 5], two observations stand out readily. First, when it comes to the four archetypes concerning products that flow, 'recycling' and 'retrieving' are the most common types of CE activity, which can be attributed to the speed of the flow (short product life cycles). This can also explain why 'rent' is not present. With regards to the five archetypes concerning products that last, 'reduce', 'repair' and 'reuse', are the most prevalent CE activities, with 'renew' also featuring across two of the models. All eight R's are present for products that last.

The R's in order of their prominence of the network analysis were: 'retrieve', 'redesign', 'reuse', 'rent', 'recycle', 'repair' and 'reduce'. It is also worth noting that 'renew' was not present at all. The most used R, i.e., 'retrieve', links to the products-that-flow archetypes, specifically the separation and sorting as well as the recycling archetypes. That 'redesign' was second most prominent is unexpected considering that it only relates to one products-that-flow archetype and to one products-that-last archetype.

The largest node cluster (in purple) bears a strong mark of the R's 'retrieve' and 'recycle'. The 'recycle' R is, not surprisingly, connected to 'waste and recycling'. The R's of 'retrieve' and 'recycle' are the types of CE activity that belong to the separation and sorting model as well as the recycling model. Both of these models are related to products that flow and therefore the focus is on reducing the impact of product systems that require a high and fast turnover of goods. Businesses such as this are represented in the major node connections between 'recycle', 'AI', 'product', 'waste and recycling', and 'process'. A key example from the CE business case collection is Ecolan which takes industrial side streams to create construction materials and fertiliser. A different example is ZenRobotics, an established software company that uses robotics to improve sorting of waste in recycling facilities. These businesses concentrate on developing industrial processes, possibly with the help of AI applications, to create products with a reduced environmental impact.

The service cluster in the analysis (in blue) was centred on the access model, which provides access to products without ownership. In connection to this, 'rent' came up as the fourth most prominent R in the analysis, which further establishes its place as the eighth R in CE business. This cluster is also tied to the performance model which focuses on service. Key examples from the CE business case collection analysed here are Vaatepuu (a clothing rental shop which also repairs and provides new sustainable products), 3StepIT (provides laptop rentals which are then recycled upon their return), and Skipperi, a peer-to-peer platform-based boat rental business. These example businesses are represented in the major node connections between 'rent', 'service', 'software', 'platform', and 'clothing'. Typically, the companies operate in platform business that mediate between consumers and products or provide traditional renting services.

The third and final cluster, mechanical engineering (in green), is built around the R's of 'redesign' and 'repair'. The strong mechanical engineering link is a connection to the hybrid model, where the repair of component parts is used to keep larger high-quality products workable. However, this also overlaps with the gap exploiter model as it is third party companies that are repairing the components rather than the original producer. A prime example from the CE business case collection is Valtra which remanufactures high quality gearboxes to its main product, tractors, whereas Konecranes has paid a lot of attention to redesigning cranes so that they would be easily serviceable and could be updated.

In summary, the type of CE business practice that has been emerging in these example cases can be clustered according to the age and size of companies, as seen in Fig. 2. These differing focuses form a complementary system between the organisations.

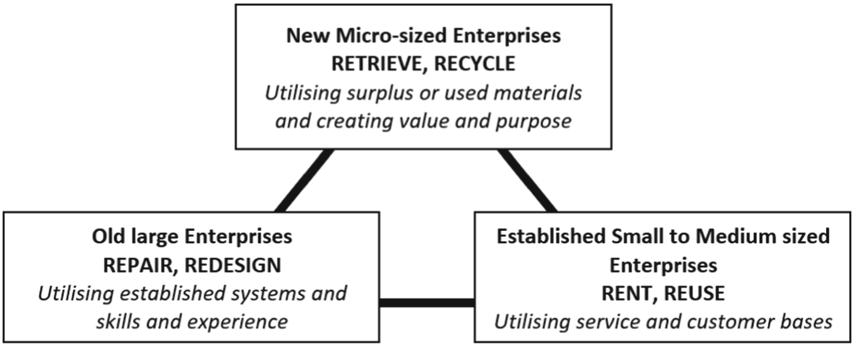



**Fig. 2.** The interplay between enterprise size and CE activities

## 5 Discussions and Conclusion

Companies have responded to the challenges of the circular economy (CE) in varying ways with circular business archetypes [4, 5] and the R's describing CE activities (Redesign, Reduce, Reuse, Renew, Repair, Recycle, and Retrieve [6] and this papers addition of Rent) providing good foundations for reviewing how companies embrace new ways of doing business. In our study, we have reviewed a sample of 41 CE business cases in Finland and applied network analysis to distinguish and connect similarities and differences across the cases. This methodology allows us to reach beyond categorisations of cases to networks of company characteristics, which we have clustered and visualised with the Gephi software [19].

The company size and the type of CE activities they have chosen to adopt is representative of the existing strengths of the business. Old large companies and established small to medium sized companies are making strides in the CE business models related to making durable products and the maximisation of product life cycle and use. Whereas new micro-sized companies are finding opportunity in the flow cycle and the wealth of resources which can be transformed and repurposed. Repurposed.

For large old companies that have established systems and are renowned for their experience and quality market offerings, to focus on repair and redesign allows them to draw upon the brand equity they have already obtained. Many of these established companies may have already been operating under the classic long-life model, producing high quality products to ensure a long lifespan. They have gained a strong reputation for producing durable high-quality goods. In their line of business, service and support are integral, making it a natural progression to focus on the repair and redesign as routes to CE business practice. However, this area of CE activity is not limited to the original providers of the products as this is also a prime area for the gap exploiter model with third parties being able to work with the high-quality product and provide repair and redesign services to ensure the duration of the product lifespan. Also, the hybrid model, where a part is being produced for the original market offering, is highly relevant. Largely this will be dependent upon if the original manufacturer provides this service and how accessible it is to the consumer, whether through availability or cost.

Established small to medium sized enterprises that have developed a consumer base and are structured around providing service elements, rent is the prime route to CE business. Here these businesses typically have lean business models which utilise technology and the opportunities that platform services pose. Along with this comes the additional option to have third parties (such as other users) to provide the market offering itself, with the enterprise being simply a facilitator. This agile route to CE business follows both the performance model and the access models, where the consumers are only interested in the service rather than the product used, removing the need for individual ownership, or providing a platform allowing reuse with the consumers buying and selling product or service.

New micro-sized enterprises find a wealth of opportunity in the retrieval and recycling of material, working on pulling materials back into the system which would otherwise have been discarded as waste. This innovative route to CE business corresponds with the separation and sorting model as well as the recycling model and, therefore, working in harmony with the bigger enterprises who are focused on maximising lifecycles and finally returning any usable material into the system and completing the CE loop.

This interplay between organisation age and size represents a connectedness in the Finnish CE marketplace. The differing strengths and dynamics of the organisations depending on their size lends itself to certain circular business archetypes and by extension CE activities. Companies seeking to develop more circular business practice can learn from this case and how their business structure may dictate which of the 8Rs are the right choice for CE development or transition. This study also found that the flow management model and the reversed logistics model is lacking representation in the analysis undertaken, which could imply that there are opportunities for business to develop in this direction, particularly with large old organisations who could seek to transform some of their traditional systems and processes towards the CE.

One potential limitation of this study is that it relied on organisations' self-reporting of their CE credentials, which could have resulted in overlooking some CE practices. This study also explored exemplary Finnish CE business cases and further research could seek to compare CE business cases internationally.

**Acknowledgements.** The authors wish to acknowledge the BLUEPRINT to a Circular Economy, which is an Interreg V A France (Channel) England project N$^{O}$206, and the MORE project funded by Business Finland.

## References

1. García-Sánchez, I., Somohano-Rodríguez, F., Amor-Esteban, V., Frías-Aceituno, J.: Which region and which sector leads the circular economy? CEBIX, a multivariant index based on business actions. J. Environ. Manage. **297**, 113299 (2021)
2. Rosa, P., Sassanelli, C.: Towards Circular Business Models: A Systematic literature review on classification frameworks and archetypes. J. Clean. Prod. **236**, 117696 (2019)
3. Pieroni, M.P., McAloone, T.C., Pigosso, D.C.: From theory to practice: systematising and testing business model archetypes for circular economy. Resour. Conserv. Recycl. **162**, 105029 (2020)
4. Haffmans, S., Van Gelder, M., Van Hinte, E., Zijlstra, Y.: Products that Flow: Circular Business Models and Design Strategies for Fast-Moving Consumer Goods. BIS Publishers, Amsterdam (2018)
5. Bakker, C., Den Hollander, M., Van Hinte, E.: Products that Last: Product Design for Circular Business Models. BIS Publishers, Amsterdam (2020)
6. Reike, D., Vermeulen, J. V., Witjes, S.: The circular economy: New or refurbished as CE 3.0? – Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resources, Conservation and Recycling 135, 246–264 (2018)
7. Guldmann, E.: Best practice examples of circular business models. Danish Environmental Protection Agency, Copenhagen (2016)
8. Lacy, P., Rutqvist, J.: Waste to wealth: The circular economy advantage. Palgrave Macmillan, Basingstoke (2015)
9. Tukker, A.: Eight types of product service systems: Eight ways to sustainability? Experiences from SusProNet. Bus. Strateg. Environ. **13**(4), 246–260 (2004)
10. Bocken, N., Ritala, P.: Six ways to build circular business models. J. Bus. Strateg. **43**(3), 184–192 (2021)
11. Azad, N., Nobahari, S., Bagheri, H., Esmaeeli, M., Rikhtegar, M.: An exploration study on factors influencing green marketing. Management Science Letters **3**, 1369–1374 (2013)
12. Bassi, F., Dias, J.G.: The use of circular economy practices in SMEs across the EU. Resour. Conserv. Recycl. **146**, 523–533 (2019)
13. Barreiro-Gen, M., Lozano, R.: How circular is the circular economy? Analysing the implementation of circular economy in organisations. Bus. Strateg. Environ. **29**, 3484–3494 (2020)
14. Katz-Gerro, T., Sintas, J.L.: Mapping circular economy activities in the European Union: Patterns of implementation and their correlates in small and medium-sized enterprises. Bus. Strateg. Environ. **28**, 485–496 (2018)
15. Garcés-Ayerbe, C., Rivera-Torres, P., Suárez-Perales, I., Leyva-de la Hiz, D. I.: Is It possible to change from a linear to a circular economy? An overview of opportunities and barriers for European small and medium-sized enterprise companies. International Journal of Environmental Research and Public Health 16, 851 (2019)
16. Sitra, https://www.sitra.fi/hankkeet/kiertotalouden-kiinnostavimmat/, last accessed 2022/05/06
17. Urbinati, A., Chiaroni, D., Chiesa, V.: Towards a new taxonomy of circular economy business models. J. Clean. Prod. **168**, 487–498 (2017)
18. Diaz, L.F., J., Bastein, T., Tukker, A.: Business model innovation for resource-efficiency, circularity and cleaner production: What 143 cases tell us. Ecol. Econ. **155**, 20–35 (2019)
19. Bastian M., Heymann S., Jacomy M.: Gephi: an open source software for exploring and manipulating networks. In: Proceedings of the International AAAI Conference on Weblogs and Social Media. Vol. 3. No. 1..(2009)

20. Jacomy, M., Venturini, T., Heymann, S., Bastian, M.: ForceAtlas2, a continuous graph layout algorithm for handy network visualization designed for the Gephi software. PLoS ONE **9**(6), e98679 (2014)
21. Blondel, V.D., Guillaume, J.L., Lambiotte, R., Lefebvre, E.: Fast unfolding of communities in large networks. J. Stat. Mech: Theory Exp. **2008**(10), P10008 (2008)
22. Lambiotte, R., Delvenne, J. C., Barahona, M.: Laplacian dynamics and multiscale modular structure in networks. arXiv preprint, arXiv:0812.1770 (2008)

# Shoving Not Nudging: A Case of Shaming 'Waster' Stickers

Katie Louise Leggett[1](✉), Minna Lammi[1,2], and Lewis Walsh[1]

[1] Anglia Ruskin University, Cambridge CB1 1PT, UK
Katie-louise.leggett@aru.ac.uk
[2] University of Helsinki, 00014 Helsinki, Finland

**Abstract.** Sustainability is centred around the concept of finding an equilibrium with regards to Earth's ability to support life and the need for economic growth. The circular economy complements this by seeking to provide a production and consumption model which seeks to use resources for as long as possible with minimal waste. This paper aims to examine householder response towards recycling campaigns using the shoving intervention strategy and subsequently the emotion of shame. The case study methodology was used on a UK campaign using negatively framed 'waster' stickers. Three secondary literature sources and two primary interviews were used for the case study analysis. Two main reactions were found because of the campaign – the feeling of being insulted and to shift the blame, with the insult indicating a level of shame. Thus, the use of shoving as an intervention strategy was found to lead to negative householder reaction, suggesting that other strategies such as nudging may be more effective in positive recycling attitudes.

**Keywords:** Recycling · Shame · Reaction · Sustainability · Circular economy

## 1 Introduction

Sustainability as a concept is a consequence of recognition of human activity and its subsequent impact on the environment, along with the existential risk that it creates for future generations [1]. At the core of sustainability therefore the focus is on the state of the Earth's biophysical environment, with regard towards the use, damage, and depletion of resources as they are not infinite. Ultimately, sustainability strives to find a steady state, so that the planet can support life as well as economic growth [2]. Thus, with the focus on sustaining life, of plants and animals as well as people, sustainability also has ethical components, based on moral claims regarding the responsibilities and obligations of both individuals and organisations. This can be taken so far as to imply sustainability is an ideology, consisting of a set of intertwined beliefs and values that determine how collective life might be better organised [3].

The desire for more sustainable consumption and production has led to a drive towards the circular economy. The circular economy is rapidly evolving, spurred on by the challenges that we are facing in modern society, from climate change and environmental devastation to social inequalities and global health concerns [4]. Circular


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 110–120, 2023.
https://doi.org/10.1007/978-981-19-9205-6_11

economy activity avoids losses that premature wasting causes and generates a range of new economic activities from the processes of recovery and reuse [5].

Thinking that waste is the problem of the government is common among individuals, which has exacerbated the global waste crisis. However, the success of recycling efforts is dependent on individuals' attitudes towards waste and waste management options. The best practice for recycling is to sort at the source, however this has proven difficult to incentivise [6].

In this paper we will look at a case from Peterborough, the UK, where the city council launched a recycling campaign trial whereby stickers were produced to be placed on recycling bins depending on the contents by the collection team. We are interested in the reaction to public shaming as a punitive measure. Although, there have been reports of negative framing being the most effective in relation to shame appeals [7, 8], studies focusing on sustainability report that a positive frame is more effective [9]; thus, in a social marketing campaign promoting recycling both opposing findings are equally likely to be encountered. We will ask whether a forced shove towards recycling can be more useful than a nudge to increase consumer recycling intention and meet consumer waste recycling targets.

## 2 Background

Sustainability is commended by an ever-growing collective ranging from individuals to international organisations [3]. With awareness of environmental concerns growing, individuals are attributing a higher value to environmentally friendly behaviours [7]. The UK government is also pushing towards an increased household recycling figure, with the past target of 50% recycling of household waste by 2020. This 50% target was not reached and has been reported at 44% [10]. In terms of UK household dry recycling levels, the previous target of 50% is becoming less likely with the level of recycling decreasing in 2020. This makes government and local authority recycling initiatives crucial in the aim of shifting UK consumer waste and recycling habits.

Social marketing is used to encourage behaviours, such as recycling, which are beneficial to society, even if they may not be useful for the individual [11]. It is largely recognised that emotions play a critical role in sustainable consumption [12]. The emotion of shame, a negative mood state, is the focus of this study [7].

With household recycling being a crucial element of the successful processing of recyclable materials to enter back into the circular production system, there are many ideas at council levels as to encouragement, with little knowledge of what emotions will see the best return in terms of positive recycling attitudes. This paper seeks to contribute to this knowledge by examining the outcome of using the emotion of shame to try and improve household recycling rates.

Firstly, literature regarding the emotion of shame will be reviewed to better understand the emotion which is central to this case, then knowledge regarding the use of positive or negative message frames shall be explored, with the stickers in this case providing a negative message frame, subsequently the value exchange matrix [13] shall be reviewed as it explores how policy makers can encourage consumers. The methodology used in this study is a case study method and provides a multi-actor perspective of the event that occurred. This allows us to conclude by identifying phenomena which occurred in this particular case.

## 3 Literature Review

This literature review begins by exploring the negative self-conscious emotion of shame, which was used in the 'waster' sticker campaign case [14]. The effects of positive versus negative message framing is then discussed. Finally, social intervention and French's (2011) value exchange matrix is reviewed.

### 3.1 Shame

In the study regarding shame in social marketing appeals by Brennan and Binney (2010), the participants described shame as being the emotion that they experience, when others who hold meaning to them are aware of any socially unacceptable behaviour they have carried out. The closer the association the more deeply the participants reported they would feel ashamed, as it would be going against that particular social group's principles [11]. It can also be argued that anticipated shame is the cause of pro-environmental actions, as whilst guilt is a post action emotion, which produces a subsequent reaction of trying to repair the perceived harm which was done; shame can occur both pre and post action [12].

Many social marketing researchers have grouped shame and guilt together rather than examining them as two separate emotions; whilst other notable studies have separated them have found distinct differences in their effectiveness when used in various marketing scenarios [7, 11, 12]. Unlike guilt which implies a negative evaluation of a specific behaviour, shame reflects a negative evaluation of one-self [15]. When people experience shame, they feel they have done wrong and that they are 'a bad person', and this can pose a threat to their moral self-image [16]. Thus, shame has the power to devalue an individual's sense of self. Therefore, shame is associated with avoidance and inhibition in moral regulation literature [17].

When it comes to how the individual will deal with the shame they are experiencing, they will behave in a way which allows them to cope with the emotion. Reactions can be placed in two categories: withdrawing from the situation (avoidance) or participating in a way which will remove the shame they feel e.g., blaming others. An important thing to note here is that the chance of each of these responses occurring depends on whether there is opportunity provided for the individual to change their actions and thus avoid any additional damage to their self-concept [7, 18].

The reasoning behind why guilt and shame are often linked, or even used synonymously, in research is that to feel shame (of the post action type) the individual must first feel guilt for what they have done, something which was also confirmed by the participant responses in Brennan and Binney's (2010) study [11]. The public awareness of the individual's guilt is what causes the shame; thus, the publicity of the actions is key to social marketing campaigns seeking to elicit and use shame. Consequently, shame is also linked to feelings of embarrassment and humiliation.

It has also been reported in Brennan and Binney's (2010) study that participants generally considered the use of shame appeals in a negative way, claiming that they are ineffective to motivate them, with many respondents reporting that they found the idea of public shaming itself unacceptable. This was such as strongly felt sentiment that many even reported that it should not be used even if it gained the desired results [11].

### 3.2 Positive Versus Negative Message Framing

Negatively framed communications can elicit anticipated shame. This anticipated shame can motivate pro-environmental behaviours, as these actions enable the individual to recover a positive self-perception. However, an individual's personal level of environmental concern is a mediating factor in the case of negative message framing, with individuals who have a higher level of environmental concern being more likely to feel anticipated shame [12].

Negative message frame has been found to be the more effective of the two opposing frames [12]. These negative messages tend to be loss-framed implying that negative repercussions will occur if the individual does not comply with the desired action [7]. If too many negative social marketing appeals are received by individuals, it has been found that this can cause a saturation effect. As many social marketing campaigns lean towards a negative frame when seeking voluntary compliance, this has led to consumers filtering out these messages, particularly for individuals with a strong level of apathy to the situation [11].

Positive social marketing appeals were found in the study by Brennan and Binney (2010) to be more effective in motivating individuals towards compliance, especially marketing campaigns which held a light-hearted note and contained and element of humour. These campaigns proved most effective at creating a 'buzz' amongst individuals and spreading word-of-mouth [11]. These positive messages tend to also be gain-framed implying positive outcomes if the individual complies with the desired behaviour [7]. Additionally in the context of sustainability messages positive emotions were more effective in motivating people to sustainably consciousness than negative emotions [9].

The study by Baek and Yoon (2017) undertaken in the USA found that in the case of appeals for water conservation, shame focused messages with loss-framing (negative) were the most effective. In the third stage of their study the focus shifted from water conservation to recycling, and it was found that the more effort invested by the individual the negative frame had a stronger fit, but less so with lower effort expenditure [7]. The study also supports the study by Duhachek et al. (2012) which also found that for shame a loss-focus was preferable in the context of health messages [8].

### 3.3 Social Interventions

In the paper we draw upon French's (2011) Value Exchange matrix. The value exchange matrix states that social interventions – particularly those by governments/policy makers are usually made up from a combination of 'nudging', which focusses around unconsciously influencing human decision making with the intended outcome of promoting voluntary behaviour change [19]. To more ostentatious interventions - referred to as 'shoving', 'smacking', and 'hugging'- which involves direct messages, legally enforced punishments, and sometimes financial rewards [13]. Some contextual examples are as follows:

- **Hugging:** Every time the household bin does not need collecting the householders receive a payment into their account *(positive, conscious decision)*
- **Nudging:** Households bins are checked spontaneously, if they are all sorted correctly the household receives a surprise rebate on their council tax when it is next due *(positive, un-conscious decision)*
- **Shoving:** Rather than weekly household bins are changed to be collected bi-weekly reducing the space the consumers can fill *(disincentive, unconscious decision)*
- **Smacking:** A weight limit imposed on household bins alongside available bin volume, householders fined for going over the weight limit *(disincentive, conscious decision)*

French's (2011) value exchange matrix is useful as it encapsulates the notion that social marketing is a multi-disciplinary field of study [13]. It also helps us highlight that, consumers are not only influenced by the approaches taken by marketers, but by the dynamic changes in the society they live [20]. Indeed, Lefebvre (2012) notes that social marketing activities often relate to the challenges that a society is facing (e.g., economic turbulence and global warming) – with successful interventions often strongly linked to the context for which interventions are applied [21]. As such, the findings of the research will not only reflect on, and evaluate, the intervention strategies utilised by Peterborough City Council, but also the context for which these intervention strategies were undertaken within.

## 4 Methodology

In this paper we utilise a case study method, a common qualitative research method used in social sciences. The case aims to increase knowledge and understanding by describing the phenomenon, its various factors and its significance. It also interprets change by interpreting the views of different actors and the meanings given to the case. A case study is appropriate when the phenomenon is complex and possibly unstructured. The data of the research is usually diverse data obtained in different ways. The case study provides detailed, intensive information on an individual case and thus helps to understand modern phenomena and answer complex, real-world questions [22, 23].

In this paper we are using a recycling campaign as a case. We will focus on the public response to the campaign. As Peters et al. (2018) emphasise, householders are key to returning recyclable materials back into the circular system, thus understanding their attitudes towards this process is fundamental to successful recycling systems [6]. Our study consists of an analysis of three secondary sources who reported on the case, along with extracts from two primary interviews which were conducted by the authors.

## 5 Case: 'Waster' and 'Recycler' Stickers

In 2018 Peterborough city council launched a 6 month, 7000 home, recycling campaign trial under the Waste and Resources Action Programme (WRAP), whereby stickers were produced to be placed on recycling bins depending on the contents found on collection day by the collection team. Red stickers were produced with a sad-face emoji and the word 'waster' on for placement on general (non-recycling) waste bins which were found to have recyclable waste inside. Green stickers were produced with a smiley-face emoji and the word 'recycler' intended for bins which were found not to have recyclables visible inside.

The reported plan was for the green 'recycler' stickers to be released a week prior to the red 'waster' stickers, however in reality the red 'waster' stickers were the ones that were released first. The public responded negatively to the trial, with many recipients of the sticker reporting feeling insulted by what they saw as a derogatory action against them [24]. The 'waster' recycling campaign caused such amongst residents that the council was forced to publicly apologise. The graphic representation of the trial and the subsequent reactions can be seen in Fig. 1.

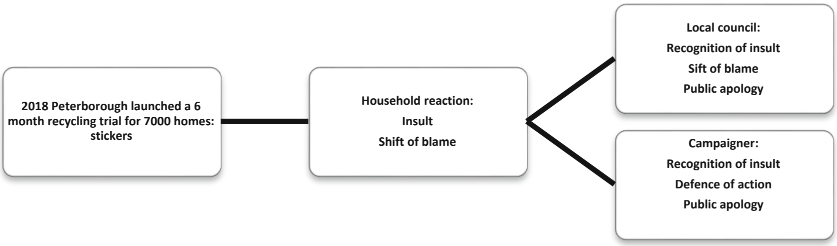



**Fig. 1.** Recycling trial and reactions to the trial

The reaction to the trail can be categorised in the following way: Consumers comments were mostly about expressing emotional reaction (Insult) and/or pointing out that the city council is itself wasting (Shift of blame). This negative reaction from the public was compounded further when it became apparent that the stickers themselves were not recyclable [24]. With many consumers wishing to dispose of the unwanted stickers and finding the irony in the fact that they could not place them in the recycling system.

Some key social media comments made by angered members of the public are cited in Jewell (2018) for the Daily Mail [24] and by the Newsroom (2018) for the Peterborough Telegraph [25] and are collated as follows:

<u>Comments showing recipient insult</u>

*"The stickers have upset a lot of people because the word waster is really insulting. It was awful to come home and find the sticker on my bin."* [24]

*"Waster is a derogatory word and I found it most insulting,"* [25]

*"It's quite insulting considering we recycle as much as we are allowed to recycle."* [25]

<u>Comments showing shift of blame by recipients</u>

*"The irony of my binman wasting time to stick sticker calling me a waster today"* [24]

*"Can we come armed with Stickers that say 'waster' if we feel your budget isn't efficient – like the sticker that has been put on my bin today"* [24]

*"@WRAP_UK thanks for my 'waster' sticker plonked on my bin this morning! The whole street has one. Is this sticker recyclable? As an avid recycler I'm miffed!"* [24]

However, it was not just the public that took to social media to express their distaste for the bin sticker recycling campaign, with many councillors also expressing their disdain over the launch of the campaign trial.

<u>Recognition of Insult</u>

*"I have had a number of comments from local people who were very unhappy with this PR stunt." – Ward councillor quote* [25]

*"Absolutely disgraceful. What kind of world are we living in where those in authority feel justified in labelling residents 'wasters'. 'Name-calling, vilifying, humiliating, public shaming: not the way for the council to meet its recycling targets. This is cack-handed & wrong." – Green councillor for the area* [24]

The reaction of the local council was first to try to explain what had happened.

*"Given that our residents are already pretty clued in when it comes to recycling I'd like to see a more sophisticated plan that reaches those people who regularly contaminate their green bins, rather than preaching to the converted with materials that are not recyclable and add to the problem rather than solving it." – Peterborough City Councillor* [25]

From the reactions we found similar type of categories as from consumers: recognition of insult as named above and shift of blame.

<u>Shift of blame</u>

*"WRAP fails to see the hypocrisy of using non-recyclable materials in its own campaign to encourage recycling?... Perhaps after this exposure they will revisit this national project and think more carefully about how to improve recycling through positive encouragement and by practicing what they preach." – Councillor* [25]

With all the backlash in the media regarding the campaign trial, both WRAP – the creators of the campaign and Peterborough country council who facilitated its roll out made statements apologising to the public. Bhashah (2018) quotes Peterborough council and WRAP both officially commenting on the case [26]:

*"We apologise to residents for any offence the emoji bin sticker may have caused – and we appreciate we should have communicated better with residents and local councillors." – Peterborough council cited by Badshah (2018)* [26]

*"It was intended that a green 'recycle' sticker with a happy face emoji would be stuck on recycling bins, and the following week a red unhappy 'waster' emoji would be stuck on residual waste bins as a reminder to recycle. Recycle Now has learnt that there was an operational issue which meant that the stickers went out in the wrong order, and that residents were delivered the red 'waster' sticker in the first instance. We understand how this may cause confusion and offence for residents and apologise for this." – WRAP cited by Badshah (2018)* [26].

With regards to the backlash from the stickers not being recyclable WRAP defended this choice by explaining that the stickers needed to be able to withstand outdoor conditions. They were subsequently cited as commenting that they recognise that the recipients of the stickers may wish to remove them and recycle them.

The interviews conducted with both a contract manager for the council and a senior waste manager help to explore this case further, from the perspective of individuals implementing the campaign trial. Firstly, an interview with the council contract manager shows the strength of the backlash received from the trial of the red 'waster' stickers and indicates shifting of the blame:

*"One of the stickers was quite controversial, it was a red sticker with a sad face, and it used the word "waster" on it, and we stuck it on the black bin and that kicked off, people hated that. So, they didn't like that judgement.*

*They didn't like…being called a waster because they used their waste bin maybe more than their recycling bin. So that definitely didn't work, and I think that was around social norming, and trying to sort of push people to think that if you don't recycle properly, it's a real anti-social thing…but it just did not work. It just did not go down well at all. We got so many complaints…*

*It appears when people… when it comes to their refuse and recycling collections and things, they can take it quite personally. And that approach did not go down well…*

*But WRAP wanted to work with us to see, they wanted to try lots of different methods to see what would work, and that definitely didn't seem to nudge people to want to do the right thing. Lots of people just took offence to it. – Interviewee 1 (Contract Manager)*

Secondly, an interview with a senior waste manager who was actively involved in the act of placing the stickers on the waste bins took the opportunity to express that they were not convinced that undertaking the task was a good idea from the outset, which was subsequently validated with the direct feedback they received from the public:

*"We were not asked about this…the wasters, that kind of language. If we were asked then perhaps, we could have come up with a different approach, but we were told… That shows our position…We didn't even know anything about this until the last minute and from that moment we told…right, we're going to have some feedback from the residents obviously, and as we expected some of the residents were not happy at all. Surely if that was me, somebody put a sticker on my bin saying 'waster' well I wouldn't like that, but we were only doing the job as we were instructed at the time. So that shows our position. Again, if that's what the council wants to do, that's what you will do as a contractor." – Interviewee 2 (Senior Waste Manager)*

It is also important to recognise that when this trial campaign was extended to other areas inside the county that the stickers were switched to more traditional signage of a green sticker with a recycling heart and a red sticker with a garbage truck symbol.

## 6 Discussion and Findings

The findings consistently highlight that not all stakeholders were engaged in the formation of the communications, therefore raising the need for all stakeholders in recycling communications to be engaged in campaign creation, as was the finding of Rakib et al. (2022) when they concluded from their study on sustainable communication that engagement from all stakeholders is proven to be essential to corporate success [9]. Key points made in the case, particularly with regards to the primary data collected from the senior waste manager and contract manager, relate to the fact that they were not consulted as to how appropriate and effective they thought the campaign would be.

The case also shows that the householders felt insulted, and this strongly implies that the emotion of shame was evident. As shame is experienced when others close to the individual become aware of socially unacceptable behaviour they have carried out [11], the highly visible 'waster' stickers highlighted the undesirable action of the householder to their neighbours and by extension community. This negative reaction to a negatively framed message is in contradiction to the findings of Baek and Yoon (2017) and Duhachek et al. (2012), who both found that negatively framed shame-based messages were most effective [7, 8]. It does however support Brennan and Binney (2010) who suggest that positively framed messages can be more effective due to the buzz they cause [11].

As the 'waster' stickers were unexpected, this meant that the householders had one of the two reactions taken from them (avoidance) which would have been a pre-action shame reaction [18]. Likewise, although anticipated shame has been found to motivate pro-environmental behaviours this was not possible with the stickers being placed on the waste-bins without warning [12]. This left them with the reaction of blaming of others [18].

Considering that the only stickers which were released were the 'waster' negatively framed stickers and the 'recycler' positively framed stickers were not launched, this meant that the only intervention strategy used in this case was that of shoving. The 'waster' stickers can be categorised as a shove intervention as using French's (2011) value exchange matrix, it is a punishment, and it was for a passive unconscious decision as the householder was not aware that it would happen when making their waste sorting choices. If the 'recycler' stickers had also been launched this would have acted as the opposite intervention strategy – nudging. Additionally had the campaign continued to run and the stickers were repeated after some time had passed, then as the householders would have been aware that the judgement was coming, this would have transformed into a hug (recycler) and smack (waster) as the waste sorting actions of the householder would have been active and conscious [13]. Which would have created a balanced social intervention campaign.

## 7 Conclusion

In conclusion the strong negative reaction of householders to the shoving social intervention 'waster' stickers highlights the strong level of shame which can be elicited in individuals when it comes to making socially unacceptable behaviours highly visible to the community around them [11]. The lack of anticipation also limited the potential for positive response, with previous studies having found that anticipated shame can motivate pro-social behaviour, suggesting that if such a campaign was to be carried out in the future, the householders may respond more beneficially if they are aware of the potential punishment or reward [12]. The lack of information regarding the campaign may have meant that given the two reactions available – avoidance or blaming of others – householders chose blaming, which might have been exacerbated as they were not aware that they could correct their behaviours and receive the reward in the future [18]. As sustainability is based on a set of interdependent social moral obligations, the use of shame, which is a social judgement-based emotion, could explain why individuals in this case felt so strongly insulted [3, 11].

A limitation of this study was that only the social intervention of shoving from the value exchange matrix could be observed. This paper closes with a call for the field to continue this trajectory by examining the remaining social interventions from French's (2011) value exchange matrix in respect to the sorting of waste in households, as the importance of proper waste management at this source is vital to the proper reclamation of materials into the circular economy system [6, 13].

Implications for the design and manufacturing community would be firstly, that materials used as a platform for encouraging recycling and more sustainable practices need to fully reflect this message, as one of the unsuccessful aspects of this case was to use stickers that could not be recycled, causing a misalignment with the principle being portrayed. Secondly, this case has highlighted that individuals can find their recycling, waste and consumption habits to be a very sensitive and personal issue, thus communications with them should be approached sympathetically. Consequently, messages using a positive frame may be more appropriate as they encourage the individual to improve their behaviour, rather than to highlight unfavourable actions which may cause negative feeling and reactions. Lastly, it is important that the consumer is an integral part of circular economy systems, from design to collection of waste resources, so that it is an intuitive process for all involved.

**Acknowledgements.** The authors wish to acknowledge the BLUEPRINT to a Circular Economy, which is an Interreg V A France (Channel) England project N$^{O}$206.

## References

1. Halliday, S., Atkins, R.: Sustainability. RIBA Publishing, Newcastle upon Tyne (2019)
2. Portney, K.E.: Sustainability. MIT Press, Massachusetts (2015)
3. Thiele, L.P.: Sustainability. Polity Press, Cambridge (2013)
4. Liu, L., Ramakrishna, S.: An Introduction to Circular Economy. Springer, Gateway East (2021)
5. Crocker, R., Saint, C. P., Chen, G., Tong., Y.: Unmaking Waste in Production and Consumption: Towards the Circular Economy. Emerald Publishing Limited, Bingley (2018)
6. Peters, S., Samarasinghe, K.: Waste management practices: innovation, waste to energy and e-EPR. In: Liu, L., Ramakrishna, S (eds.) An Introduction to Circular Economy. Springer, Gateway East (2021)
7. Baek, T.H., Yoon, S.: Guilt and shame: environmental message framing effects. Journal of Advertising **46**(3), 440–453 (2017)
8. Duhachek, A., Agrawal, N., Han, D.: Guilt versus shame: coping, fluency, and framing in the effectiveness of responsible drinking messages. J. Mark. Res. **49**(6), 928–941 (2012)
9. Rakib, M., Chang, H.: Effective sustainability messages triggering consumer emotion and action: an application of the social cognitive theory and the dual-process model. Sustainability **14**(5), 2525 (2022)
10. UK Government, Department for Environmental Food and Rural Affairs: Progress report on recycling and recovery targets for England 2020. https://www.gov.uk/government/publications/progress-report-on-recycling-and-recovery-targets-for-england-2020/progress-report-on-recycling-and-recovery-targets-for-england-2020, last accessed 17 Mar. 2022
11. Brennan, L., Binney, W.: Fear, guilt and shame appeals in social marketing. J. Bus. Res. **62**(2), 140–146 (2010)
12. Amatulli, C., De Angelis, M., Peluso, A.M., Soscia, I., Guido, G.: The effect of negative message framing on green consumption: an investigation of the role of shame. J. Bus. Ethics **157**(4), 1111–1132 (2017)

13. French, J.: Why nudging is not enough. J. Soc. Mark. **1**(2), 154–152 (2011)
14. Brennan, L., Pochun, T., Parker, L.: Social marketing with fear, guilt and shame. In: Social Marketing and Advertising in the Age of Social Media. Edward Elgar Publishing pp. 86–101 (2020)
15. Rothmund, T., Baumert, A.: Shame on me: implicit assessment of negative moral self-evaluation in shame-proneness. Soc. Psychol. Pers. Sci. **5**(2), 195–202 (2014)
16. Gausel, N., Leach, C.W.: Concern for self-image and social image in the management of moral failure: Rethinking shame. Eur. J. Soc. Psychol. **41**, 468–478 (2011)
17. Sheikh, S., Janoff-Bulman, R.: The "shoulds" and "should nots" of moral emotions: a self-regulatory perspective on shame and guilt. Pers. & Soc. Psychol. Bull. **36**(2), 213-224 (2010)
18. Korkea-Aho, E.: Flight shame: shame as a tool to change consumer behavior (2019)
19. Ölander, F., Thøgersen, J.: Informing versus nudging in environmental policy. J. Consum. Policy **37**(3), 341–356 (2014)
20. Dibb, S.: Up, up and away: social marketing breaks free. J. Mark. Manag. **30**(11–12), 1159–1185 (2014)
21. Lefebvre, R.C.: Transformative social marketing: co-creating the social marketing discipline and brand. J. Soc. Mark. **2**(2), 118–129 (2012)
22. Yin, R.K.: Case Study Research, 4th edn. SAGE, London (2009)
23. Tetnowski, J.: Qualitative case study research design. Perspect. Fluen. Fluen. Disord. **25**(1), 39–45 (2015)
24. Jewell, B.: https://www.dailymail.co.uk/news/article-6449369/Fury-council-brands-householders-wasters-derogatory-emoji-stickers-left-wheelie-bins.html. Accessed 7 May 2022
25. Newsroom, T.: https://www.peterboroughtoday.co.uk/news/insulting-and-derogatory-stickers-which-aim-encourage-peterborough-residents-recycle-are-not-recyclable-173894. Accessed 7 May 2022
26. Badshah, N.: https://www.theguardian.com/uk-news/2018/dec/01/peterborough-council-apologises-over-waster-recycling-stickers#:~:text=Peterborough%20city%20council%20has%20apologised,on%20their%20black%20wheelie%20bins. Accessed 7 May 2022

# Sustainability-Related Challenges in Customer-Supplier Relationships in the Manufacturing Industry

Tuija Rantala(✉), Jyri Hanski, Teuvo Uusitalo, and Jukka Hemilä

VTT Technical Research Centre of Finland, Visiokatu 4, 33101 Tampere, Finland
tuija.rantala@vtt.fi

**Abstract.** In the literature, sustainability in customer-supplier relationships from the perspective of manufacturing companies has not been extensively studied, although there is pressure both within and outside of the companies. This paper studies how manufacturing companies view sustainability in their business and the sustainability-related challenges in customer-supplier relationships. We explore the theme by presenting findings from 12 recent interviews with five manufacturing companies. The interviewees saw sustainability as containing a future-oriented perspective of sustainable operations and a practical point of view. Sustainability-related challenges in customer-supplier relationships were mentioned as turning sustainability into customer value and financial profit, identifying customers' sustainability needs, managing data related to sustainability, and managing sustainability through the value chain. The paper presents practical perspectives on sustainability in manufacturing companies and a framework for identifying customer needs related to sustainability. Managerial and theoretical implications consist of clarifying scattered viewpoints about sustainability in customer-supplier relationships in the manufacturing industry.

**Keywords:** Sustainability · Manufacturing companies · Customer-supplier relationships

## 1 Introduction

The manufacturing industry has an important role in reducing resource use, waste, and emissions (see IPCC, 2014). Manufacturing and construction are responsible for a fifth of global total greenhouse gas emissions (World Bank, 2017). A drastic change toward sustainability is needed, as pointed out by the research community, industry, and governing bodies and politicians. EU-based industries are aiming for a low-carbon economy in line with the EU's climate neutral by 2050 and Fit for 55 targets (European Commission, 2021). Companies can approach low-carbon targets by incremental reductions in greenhouse gas (GHG) emissions, utilizing clean energy, energy efficiency, and new processes and technologies. For manufacturing, new processes and technologies include electrification (green electricity and storage), green hydrogen, and $CO_2$ capture and storage.


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 121–132, 2023.
https://doi.org/10.1007/978-981-19-9205-6_12

The EU's Twin Transition aims at utilizing digital technologies and adopting a circular economy model for an environmentally friendly and low-carbon economy. With the emergence of the twin transition, the manufacturing industry is investing heavily in new IT and green technologies such as electrification, batteries, and renewables production. However, digitalization and green technologies consume vast amounts of raw materials, several of which are considered critical (Bobba et al., 2020; Eerola et al., 2021). Furthermore, the IT sector has a considerable energy and environmental footprint (Eerola et al., 2021). In a broader sense, manufacturing companies are dependent on the availability of different raw materials, processed intermediaries, components, and end products, often excavated, processed, and manufactured outside the EU (ibid.).

The lack of a comprehensive definition of sustainability has been a fundamental challenge in moving the field forward (Tricco et al., 2016). Moore et al. (2017) concluded the following in their extensive literature search on sustainability definitions: 'A comprehensive definition of sustainability that includes five constructs: (1) after a defined period, (2) the program, clinical intervention, and/or implementation strategies continue to be delivered, and/or (3) individual behaviour change (i.e., clinician, patient) is maintained; (4) the program and individual behaviour change may evolve or adapt while (5) continuing to produce benefits for individuals/systems.' Sustainability-related actions aim to renew or improve products, services, and technological or organizational processes that deliver an improved economic, environmental, and social performance, both in the short and long term, and can generate positive sustainability impacts (Bos-Brouwers, 2010).

Sustainability has been studied from several perspectives in the manufacturing industry, e.g. drivers (see Aboelmaged, 2018) and barriers (see Orji, 2019; Koho et al., 2015), business potential (see Valkokari et al., 2014) relationships between lean manufacturing, industry 4.0, and sustainability (see Varela et al., 2019; Ejsmont et al., 2020), the lean energy-saving and emission-reduction strategy (see Cai et al., 2019), sustainability of manufacturing processes (Jamwal et al., 2021), and the role of intellectual property (Eppinger et al., 2021).

The circular economy has been identified as a cornerstone of sustainability transition, but the relationship between the circular economy and sustainability in manufacturing companies is vague. The circular economy can be used as a route to progress toward sustainable development (Shroeder et al., 2019). The Ellen MacArthur Foundation (2015) defines a circular economy as 'an industrial economy that is restorative by intention and design'. Bjørnbet et al. (2021) concluded that the research on the circular economy in manufacturing companies has moved from purely conceptual work to empirical studies and from research to implementation tools. However, in empirical studies, the impact of sustainability is mainly addressed through the environmental dimension with narrow approaches (ibid.). The authors suggested that more empirical research is still needed to create the big picture of sustainability in manufacturing companies (ibid.).

Sustainability in customer-supplier relationships is not widely studied in the manufacturing industry. There is a need for long-term business planning and new frameworks and models to answer customer needs for sustainability and not only from the circular economy perspective. *This study is about sustainability-related challenges in customer-supplier relationships in the manufacturing industry. The paper presents practical findings from interviews and a framework to recognize sustainability-related customer needs in the manufacturing industry.*

## 2 Literature Review

### 2.1 Customer-Supplier Relationships in the Manufacturing Industry

In the early 21st century, companies started to search for new forms of external cooperation and opened their innovation processes in both directions in the value chain – upstream toward suppliers and downstream toward customers (Paasi et al., 2012). Customer-supplier management practices have been divergent. For example, customers may have an 'adversarial' attitude towards their suppliers – valuing primarily the short-term price of supplier's wares and how much risk they are willing to take associated with variations in supply and demand. This is very different from symbiotic arrangements where customers also share knowledge with suppliers, help in solving problems, and innovate together (ibid.). Both attitudes still exist. However, digitalization, e.g. Internet of Things (IoT) applications, social media, and e-commerce, has brought customers into closer collaboration with their suppliers. Nowadays, customer experience, customer journey, customer orientation, customer value, seller-buyer interactions, and customer engagement are being highlighted, and customer-supplier relationships are more important (see Alhonen et al., 2018; Hakanen et al., 2014; Becker and Jaakkola, 2020).

Sustainability actions must respond to the needs of the present moment with a commitment to future capacity and a compromise between increasing economic gains while minimizing social and environmental consequences (Helleno et al., 2017). Organizational change management for sustainability is widely discussed and essential. Therefore, motivated industrial companies are considering the environmental, social, and economic impacts of their operations as well as changing their activities (Orji, 2019). Companies may struggle to implement effective organizational change management practices and reach sustainability goals. It is important to recognize the barriers and drivers of sustainable performance that have the highest influence on a company to foster change towards sustainability (Lozano and Haartman, 2018).

Within the manufacturing industries, customers are setting several sustainability requirements for their suppliers. Manufacturing companies must offer a higher return on investment, and, at the same time, environmental impacts must be reduced (Machado et al., 2020). Depending on the size of the customer, the requirements and sustainability goals differ. The literature suggests that large firms often focus on activities related to maximizing material efficiency, creating value from waste, and moving to renewable energy, which are all linked to cost savings (Hernández-Chea et al., 2021). In addition, sustainability is highly related to operations – for example, employee wellness, ensuring working conditions, responsible purchasing, etc. Customers may outsource many operations to their suppliers. Then suppliers provide not only raw materials and finished products but also transportation, energy, packaging, design, and recycling services (Valkokari et al., 2014). Sustainability can be part of everything firms do. Large firms, especially those listed on the stock exchanges, have clear sustainability goals and are required to report their sustainability programs and activities. Therefore, large firms typically use different auditing methods for their supplier. Auditing methods can have different targets, depending on the focus of auditing. One example is SMETA (Sedex Members Ethical Trade Audit), which is the most widely used social audit in the world. SMETA is a social audit methodology that enables businesses to assess their sites and suppliers to understand the working conditions in their supply chain. Social audits enable businesses to assess their suppliers, monitor the health and safety of workers, and signal zero tolerance for human rights abuses such as child and forced labour. Once an audit is complete, the buyer and supplier businesses can work together to address any issues, based on a Corrective Action Plan (CAPR).

## 2.2 Understanding Sustainability and Value Creation in Manufacturing Companies

The main goal of sustainability is to meet current needs without compromising the ecological systems, social justice, and welfare of future generations (Brundtland, 1987; Jorna et al., 2009). For manufacturing companies, this implies that they must take into account not just economic goals, but also meet environmental and social goals in carrying out business while recognising that economic, environmental, and social impacts occur at all life cycle stages in their value network (Rantala et al., 2022). Additionally, sustainable manufacturing focuses on the efficient and effective use of natural resources by creating products and solutions that can satisfy economic, environmental, and social objectives while continuing to improve the quality of human life (Garetti and Taisch, 2012; Uusitalo et al., 2017). In manufacturing practice, sustainability has implied a focus on minimising the environmental impacts of production, following social norms, promoting well-being, and creating business benefits (Schiederig et al., 2012; Buys et al., 2014).

In manufacturing, value is generated through activities and interactions between suppliers, manufacturers, customers, and other stakeholders. Sustainable value creation requires the integration of the three dimensions of sustainability – social, environmental, and economic – in a manner that balances value creation for all stakeholders, including the environment and society at all levels and through all activities of the business (Bocken et al., 2015; Badurdeen and Jawahir, 2017).

The manufacturing industry has a considerable environmental, social, and economic impact, and the transition to a sustainable operating model is of utmost importance to save ecological systems and ensure social justice and the welfare of future generations. However, measuring the comprehensive sustainability impact of companies and their value network is challenging and resource-consuming, and few reliable frameworks exist to support this task (e.g., Pande and Adil, 2022). The sustainability actions of most companies focus on certain limited indicators or trying to understand and comply with current and future legislation or pressing customer demands (Rantala et al., 2022).

## 2.3 Challenges and Value Creation of Sustainability-Related Actions

Stakeholders expect companies to develop and take sustainability-related actions to achieve their economic, environmental, and social goals. Challenges and barriers to sustainability-related actions can be categorized into environmental, economic, social, institutional, technological, informational, supply chain, and organizational factors (Tura et al., 2019). Koho et al. (2015) studied challenges and the general situation of sustainability in the manufacturing industry and concluded that the objectives of sustainable development are not fully realized and the integration of sustainability and decision-making needs to be increased. They mentioned that lack of metrics, implications, demand, understanding, and awareness are the key challenges for manufacturing companies to proceed with sustainability-related actions (Koho et al., 2015). According to a literature review by Lood and Säfsten (2022), the most frequently mentioned barriers to sustainable manufacturing in SMEs include lack of access to external technical knowledge to adopt sustainable manufacturing practices, low skilled labour, lack of awareness of the benefits derived from sustainable manufacturing practices, lack of financial resources, managers' misunderstandings and pessimistic preconceptions, lack of time for planning, execution and review of sustainable manufacturing practices, little knowledge on sustainability in SMEs, difficulties accessing financial capital, resistance to change, lack of effective legislation and/or weak regulatory environment, high investment costs, and low returns of environmental technologies.

Identified barriers to sustainable manufacturing are largely in line with barriers to a circular economy in manufacturing. Barriers to a circular economy include costs (e.g. high investment or scrap material costs), measuring long-term benefits of investment, customer response and long-term demand, lack of incentives (e.g. in the form of financial support or taxes), complex and overlapping regulation, lack of appropriate partners and resources, conflict with existing business culture and lack of management support, lack of public awareness, technical skills and knowledge, and available systems or technology (Tura et al., 2019; Kumar et al., 2019).

## 3 Methodology

The case study was chosen as the method for this study because of its suitability for situations that include complex and multiple variables and processes (Yin, 2014). Qualitative data consists of 12 semi-structured interviews in 5 different companies in the machine-building and electronics manufacturing industry (Table 1). There were 2–4 interviews with each company to better understand the business of the case companies. The interviewees represented different positions in the company, preferably in management, sales, and R&D.

The case companies are operating in b-to-b markets. Some of them also operate in b-to-c markets, but the focus of this research is on their b-to-b relationships. The interviews were made from September to November 2021. They were recorded and comprehensive notes were taken. The duration of a typical interview was 1 to 1.5 h, and each involved 1–3 interviewers. Because the study is partly explorative and the meanings of concepts (e.g. sustainability) needed to be negotiated with the interviewees, semi-structured theme interviews were chosen as the main source of empirical material. The interviews went beyond sustainability and customer-supplier relationships to understand their business. The results have been elaborated in several discussions with researchers and in a workshop for analysing the research results with the company and researcher representatives in January 2022.

**Table 1.** Interviewed companies, their main products and services, number of interviewees, and interview dates.

| Company | Main products and services | No of the interviewees and their roles | Interview date |
|---|---|---|---|
| A | Forestry machinery | 2 (Director R&D, sales, marketing) | September 2021 |
| B | Machine equipment | 2 (Director service dev., R&D, data analyst) | September 2021 |
| C | Packaging machinery | 3 (Management plant, service dev., R&D) | October 2021 |
| D | Glass treatment machinery | 4 (Management business unit, R&D, software, product management) | October 2021 |
| E | Sheet metal processing machinery | 1 (Management, R&D, software) | November 2021 |

### 3.1 Research Question

The study aims to create an understanding of the main sustainability-related challenges in customer-supplier relationships in the manufacturing industry. Thus, we pose two research questions:

1. How do manufacturing companies understand the term 'sustainability' in their business?
2. What are the main sustainability-related challenges in customer-supplier relationships in the manufacturing industry?

In this paper, manufacturing refers to companies manufacturing machinery for business-to-business customers.

## 4 Results

### 4.1 The Definitions of Sustainability in Manufacturing Companies

Sustainability as a term is seen to be very difficult to describe, and it has several different meanings for the interviewees. For example, it was seen as accelerating products and processes through data and improving communications. The interviewees considered 'sustainability' a challenging term. The interviewees looked at 'sustainability' from a future-oriented perspective of sustainable operations or a practical point of view. Examples of future-oriented sustainable operations that were mentioned by the interviewees focused on the big picture, long-term planning, persevering operations, clear goals, and brand image. Customer care, long life cycles, the durability of machines and products, safety issues, warranty matters, and well-being were examples from a practical point of view.

Below, there are examples of both future-oriented and practical perspectives of sustainability according to the interviewees:

*"Long-term sustainability of operations, building our and customer's business on long-term goals as well as right-minded actions in practice."*

*"Doing what's promised to customers, warranty matters, goodwill operations, treating staff according to all the rules of art."*

## 4.2 Sustainability and Value Creation

According to the interviewees, actors driving the sustainability agenda in the manufacturing industry are mainly customers or customers of large customer companies in the industry. Large companies may be the driver, but contractors are not happy about increasing cost levels. For example, decreasing CO2 emissions will cost.

Our results show that **turning sustainability into customer value** is a challenge in the manufacturing industry. Forefront customers understand better technological development, data utilization, and the meaning of sustainability. However, the situation varies greatly. Many companies are still at a stage where they are trying to understand the meaning of sustainability for themselves in general. The interviewees identified the potential for value creation, for example, in speeding up the customer's decision process, decreasing life cycle costs, and offering data-based services. Sustainability was seen to have a great indirect effect on business. An interviewee described the benefits of sustainability for business as follows:

*'Sustainability benefits reputation, improved reputation benefits business.'*

When we asked about converting **sustainability solutions into financial profit**, the interviewees mentioned typical qualitative values. Seeing a slightly bigger picture than a machine perspective was considered important. Long-term operations, long-term customer relationships, and life cycle management were potential ways to convert sustainability into financial profit. An interviewee clarified that mutual benefits of product lifecycle management are very important, as there are economic benefits not only for the buyer but also for the seller. From the sales perspective, sales arguments might be seen as technical. This has a large effect on transferring sustainability into monetary value. The interviewees mentioned that it should be possible to concretize measurements throughout the supply and value chain and have a jointly agreed course of action. An interviewee gave an example of how challenging it is to create value from sustainability, as follows:

*'It doesn't matter to our business yet, even though all our customers write in capital letters about their environmental policy and so on. When we're out there trading, it's going to mean zero. It's like roughly saying that it's the price that counts when you talk about something like this... If we present our life cycle there with small life cycles or sensible lifecycle costs or other things like this, then they don't listen to them.'*

## 4.3 Sustainability-Related Challenges in Customer-Supplier Relationships

Based on our results, **data** are a crucial part of sustainability, as they enable sustainability-related actions, measuring, and verifying sustainability. Many challenges of sustainability in customer-supplier relationships are on some level related to data and according to our study, those can be categorized into three categories – *process, business, and change management-related challenges.* There can be process-related challenges, for example, data acquisition, quality, and security issues. Business-related challenges include challenges to identify customer needs and best collaboration partners, communication and sales-related challenges, and earning logic-related challenges. When communicating to customers the value of data that improves sustainability, it is important to focus on the right thing and have a clear message for each customer. The interviewees mentioned that customers are traditional in their industry, and it is challenging to highlight the right value to each person in the customer organization. The customer value must be negotiated at different levels of the customer organization. Change management challenges are related to acceptance issues, high expectations, and communication in the supply chain.

**Sustainability perspectives in the value chain** are essential for manufacturing companies. Production, operations, and after-sales depend on several actors in the manufacturing value chain. There are many different suppliers, service providers, and other actors in the ecosystem whose opinions and behaviour also affect the overall sustainability realization. However, agreed procedures or ways to collaborate from the sustainability perspective are usually missing. The challenges of customer-supplier relationships from the sustainability perspective were described as follows by an interviewee:

*'Long-term supplier relationships, there should be written instructions for suppliers in the future.'*

Another challenge was the **negotiation position** of smaller companies. Smaller companies may not have the power to influence sustainability aspects. The interviewees mentioned the difficulty in identifying **customer needs**. For example, customers request measures to protect the environment, minimize environmental impact, and improve energy efficiency. Additionally, a regular procedure is to ask about liability issues, conformity to the law, no use of child labour, safety, and health issues. An interviewee clarified the situation as follows:

*'Customers ask about safety, environment, quality issues. For example, have you committed an environmental crime for which you have been convicted?'*

Based on our research results, customer needs related to sustainability are valuable to identify already in the early phases of the company's path toward sustainability. This could be done through a straightforward table, where the customer segments and their characteristics, sustainability needs, auditing requirements, required skills and resources, and responsible person are identified (Table 2).

**Table 2.** Example of a tool for identifying customer needs related to sustainability in the manufacturing industry.

| Customer segment | Sustainability needs | Auditing requirements | Required skills and resources | Responsible person |
|---|---|---|---|---|
| Segment A | CO2 emission limits and special requirements for the supply chain | SMETA | SMETA auditing content understanding and resources | Person N.N |

## 5 Discussion and Conclusions

The COVID-19 pandemic and Russia's invasion of Ukraine are creating short-term disruptions and provoking long-term changes in how the world lives and does business. At the same time, companies need to cope with sustainability-related aspects in a very volatile business environment. Increasing awareness of life cycle impacts of human activity on nature, climate change adaptation and mitigation, biodiversity loss, social impacts of production and energy and raw materials availability are just some examples of perspectives that manufacturing companies must consider in their actions.

According to our findings, the manufacturing companies' operating environment may not be ready to accept new kinds of operating models with a sustainability focus. The situation hasn't changed so much since Koho et al.'s study in 2015, and our findings are in accordance with the authors. There is, for example, a lack of metrics, demand, understanding, and high costs still based on our findings (Koho et al., 2015; Tura et al., 2019; Kumar et al., 2019). In addition, there is a need for informing the whole value chain (internally, delivery chain, sales partners, private dealers, and customers) when changing the operating mode towards sustainability. When the company focuses on improving its sustainability, it might not be that easy. As one interviewee mentioned:

*'The idea is very easy, but practical implementation more difficult.'*

The results show that challenges of sustainability in customer-supplier relationships can be related to the whole value chain, although the actual purchase is done between two companies. Sustainability is such a multifaceted concept that it relates to several different aspects, e.g. raw materials, components, value chain, customer-supplier relationship, subcontractors, and life cycle.

There are many methods and frameworks available for sustainability assessment and reporting, which helps practitioners to select development areas for realizing sustainability in their internal operations. In an ideal situation, the whole supply chain supports common sustainability goals. Auditing methods (like SMETA) can be used for ensuring suppliers' sustainability and responsibility concerns. Optimally, the firm has perfect visibility of the key sustainability metrics of its operations and optimizes its operations from a sustainability perspective. However, in practice, there are many obstacles and challenges when developing sustainability. Companies focus on a limited view of sustainability that could be low-hanging fruit due to easily available data through existing reporting processes. There is a clear need for a sustainability framework that guides the formulation of sustainability strategy in manufacturing companies and supports the strategy implementation process. A holistic sustainability transition framework should cover the relevant part of the company value chain and key aspects of sustainability. It should also provide companies with a tailored sustainability transition roadmap, or at least goals for reaching sustainability.

Many manufacturers are still in the learning phase of what sustainability could mean for their operations. Sustainability is perhaps measured using metrics from sustainability reporting standards and is an essential part of the brand image but does not yet translate to the level of operations and product or service design. Forerunner companies measure sustainability through multiple comprehensive standardized reporting principles or audits and modify their products, organizations, and strategies to improve their performance.

Investments in sustainability might be hard to turn profitable. In some industry sectors, firms are forced to invest in sustainability to reach the minimum standards required by owners, customers, legislation, or other stakeholders. If customers are requesting sustainable solutions, then it is easier to turn investments profitable. Manufacturing industries are mostly on the right track nowadays, as they are investing in and implementing sustainability in their operations. The entire industry can be changed, and transition needs steps of every size.

The paper presents practical findings from interviews of manufacturing companies and a framework to recognize sustainability-related customer needs in the manufacturing industry. These are valuable for company managers to plan their sustainability actions in the future. Our explorative study with its limited sample only scratches the surface, but it opens up several interesting paths to take in the future. More in-depth studies are needed to develop a holistic sustainability transition framework. Thus, more in-depth studies on the sustainability of customer-supplier relationships in different industry sectors and company sizes may provide a better understanding. Formulating a sustainability transition roadmap for companies would support both focusing on the right and valuable actions as well as making better decisions.

**Acknowledgements.** The authors would like to thank all the parties behind the DataAsset (Sustainable data-based business for the manufacturing industry) project, as well as Business Finland for its support of this study.

## References

Aboelmaged, M.: The drivers of sustainable manufacturing practices in Egyptian SMEs and their impact on competitive capabilities: a PLS-SEM model. J. Clean. Prod. **175**, 207–221 (2018)

Alhonen, M., Alamäki, A., Aunimo, L., Hallikainen, H., Korpela, P., Rantala, T., and Vuori, J.: Value creation through the integration of sales and marketing: Smarketing. Haaga-Helia Publications 1/2018, 30 (2018)

Badurdeen, F., Jawahir, I.S.: Strategies for value creation through sustainable manufacturing. In: Procedia Manufacturing, 14th Global Conference on Sustainable Manufacturing, GCSM 3–5 October 2016, Stellenbosch, South Africa, 8(January 1, 2017), 20–27 (2017)

Becker, L., Jaakkola, E.: Customer experience: fundamental premises and implications for research. J. Acad. Mark. Sci. **48**(4), 630–648 (2020). https://doi.org/10.1007/s11747-019-00718-x

Bjørnbet, M.M, Skaar, C., Fet, A.M, Schulte, K.Ø.: Circular economy in manufacturing companies: a review of case study literature. J. Clean. Prod. **294**(126268), 14 (2021)
Bobba, S., Carrara, S., Huisman, J., Mathieux, F., Pavel, C.: Critical raw materials for strategic technologies and sectors in the EU—a foresight study. In: European Commission. Luxemburg Publication Office of the European Union (2020)
Bocken, N.M.P., Rana, P., Short, S.W.: Value mapping for sustainable business thinking. J. Ind. Prod. Eng. **32**(1), 88–102 (2015)
Bos-Brouwers, H.E.J.: Corporate sustainability and innovation in SMEs: evidence of themes and activities in practice. Bus. Strateg. Environ. **19**(7), 417–435 (2010)
Brundtland, G.H.: Our Common Future, World Commission on Environment and Development. Oxford United Press, New York, pp. 414–423 (1987)
Buys, L., Mengersen, K., Johnson, S., Buuren, N.V., Chauvin, A.: Creating a sustainability scorecard as a predictive tool for measuring the complex social, economic and environmental impacts of industries, a case study: assessing the viability and sustainability of the dairy company A. J. Environ. Manage. **133**, 184–192 (2014)
Cai, W., et al.: Promoting sustainability of manufacturing industry through the lean energy-saving and emission-reduction strategy. Sci. Total Environ. **665**, 23–32 (2019)
Eerola, T., Eilu, P., Hanski, J., Horn, S., Judl, J., Karhu, M., Kivikytö-Reponen, P., Lintinen, P., Långbacka, B.: Digitalization and natural resources, GTK Open File Research Report 50/2021 (2021)
Ejsmont, K., Gladysz, B., Kluczek, A.: Impact of Industry 4.0 on sustainability—bibliometric literature review. Sustainability **12**(5650), 29 (2020)
Ellen MacArthur Foundation: Towards a circular economy. Business rationale for an accelerated transition. https://ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition (2015). Accessed 26 Apr. 2022
Eppinger, E., Jain, A., Vimalnath, P., Gurtoo, A., Tietze, F., Chea, R.H.: Sustainability transitions in manufacturing: the role of intellectual property. Curr. Opin. Environ. Sustain. **49**, 118–126 (2021)
European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0550&from=EN (2021). Accessed 26 Apr. 2022
Garetti, M., Taisch, M.: Sustainable manufacturing: trends and research challenges. Prod. Plan. & Control. **23**(2–3), 83–104 (2012). Taylor & Francis Group
Hakanen, T., Kansola, M., Valkokari, K.: Acquiring customer knowledge to enhance servitization of industrial companies. In: Lay, G. (ed.) Servitization in Industry, pp. 191–209. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-06935-7_12
Helleno, A.L., de Moraes, A.J.I., Simon, A.T.: Integrating sustainability indicators and Lean Manufacturing to assess manufacturing processes: application case studies in Brazilian industry. J. Clean. Prod. **153**, 405–416 (2017)
Hernández-Chea, R., Jain, A., Bocken, N.M.P., Gurtoo, A.: The business model in sustainability transitions: a conceptualization. Sustainability **13**, 5763 (2021)
IPCC AR5 Climate Change. Mitigation of Climate Change, https://www.ipcc.ch/report/ar5/syr/ (2014). Accessed 26 Apr. 2022
Jamwal, A., Agrawal, R., Sharma, M., Giallanza, A.: Industry 4.0 Technologies for manufacturing sustainability: a systematic review and future research directions. Appl. Sci. **11**(12), 5725 (2021)
Jorna, R.J., Hadders, H., Faber, N.: Sustainability, learning, adaption and knowledge processing. Knowl. Manag. Organ. Learn. **4**, 369–384 (2009)
Koho, M., Tapaninaho, M., Heilala, J., Torvinen, S.: Towards a concept for realizing sustainability in the manufacturing industry. J. Ind. Prod. Eng. **32**(1), 12–22 (2015)
Kumar, V., Sezersan, I., Garza-Reyes, J.A., Gonzalez, E.D.R.S., Al-Shboul, M.A.: Circular economy in the manufacturing sector: benefits, opportunities and barriers. Manag. Cecis. **57**(4), 1067–1086 (2019)

Lood, C., Säfsten, K.: Barriers and enablers for the adoption of sustainable manufacturing by manufacturing SMEs. Sustainability **14**(2364), 1–34 (2022)

Lozano, R., von Haartman, R.: Reinforcing the holistic perspective of sustainability: analysis of the importance of sustainability drivers in organizations. Corp. Soc. Responsib. Environ. Manag. **25**, 508–522 (2018)

Machado, C.G., Winroth, M.P., da Silva, E.H.D.R.: Sustainable manufacturing in Industry 4.0: an emerging research agenda. Int. J. Prod. Res. **58**(5), 1462–1484 (2020)

Moore, J.E., Mascarenhas, A., Bain, J., Straus, S.E.: Developing a comprehensive definition of sustainability. Implement. Sci. **12**, 110 (2017). https://doi.org/10.1186/s13012-017-0637-1

Orji, I.J.: Examining barriers to organizational change for sustainability and drivers of sustainable performance in the metal manufacturing industry. Resour. Conserv. Recycl. **140**, 102–114 (2019)

Paasi, J., Luoma, T., Valkokari, K., Lee, N.: Knowledge and intellectual property management in customer-supplier relationships. In: Tidd, J. (ed.) Exploiting Intellectual Property to Promote Innovation and Create Value, World Scientific Publishing. Series on Technology Management, vol. 29, pp. 195–22 (2012)

Pande, B., Adil, G.K.: Assessment of the current state of sustainability in a manufacturing firm. Int. J. Product. Perform. Manag. **71**(4), 1254–1276 (2022)

Rantala, T., Hanski, J., Uusitalo, T., & Hemilä, J.: Role of sustainability data in manufacturing companies. In: Proceedings of the XXXIII ISPIM Innovation Conference in Copenhagen, Denmark 5–8 June 2022 (2022)

Schiederig, T., Tietze, F., Herstatt, C.: Green innovation in technology and innovation management—an exploratory literature review. R&D Manag. **42**(2), 180–192 (2012)

Schroeder, P., Anggraeni, K., Weber, U.: The relevance of circular economy practices to the sustainable development goals. J. Ind. Ecol. **23**(1), 77–95 (2019)

Tricco, A., Ashoor, H., Cardoso, R., MacDonald, H., Cogo, E., Kastner, M., Perrier, L., McKibbon, A., Grimshaw, J.M, Straus, S.E.: Sustainability of knowledge translation interventions in healthcare decision-making: a scoping review. Implement. Sci. **11**(55) (2016)

Tura, N., Hanski, J., Ahola, T., Ståhle, M., Piiparinen, S., Valkokari, P.: Unlocking circular business: a framework of barriers and drivers. J. Clean. Prod. **212**(1 March 2019), 90–98 (2019)

Uusitalo, T., Rana, P., Granados, M.H., Macchi, M.: Sustainable manufacturing: challenges, approaches and a roadmap. In: Value Networks in Manufacturing, pp. 27–41 (2017)

Valkokari, K., et al.: Road-mapping the business potential of sustainability within the European manufacturing industry. Foresight **16**(2014), 4 (2014)

Varela, L., Araújo, A., Ávila, P., Castro, H., Putnik, G.: Evaluation of the relation between lean manufacturing, Industry 4.0, and sustainability. Sustainability **11**, 1439 (2019). https://doi.org/10.3390/su11051439

World Bank 3.10 World Development Indicators: Carbon dioxide emissions by sector. http://wdi.worldbank.org/table/3.10 (2017). Accessed 26 Apr. 2022

Yin R.K.: Case study research: design and methods, 5th ed.. Sage Publications, Thousand Oaks, CA, p. 282 (2014)

# Archetypes of Business Models for Circular Economy: A Classification Approach and Value Perspective

Tirufat D. Woldeyes(✉), Moreno Muffatto, and Francesco Ferrati

School of Entrepreneurship, Department of Industrial Engineering, University of Padova, Padova, Italy
tirufatdejene.woldeyes@phd.unipd.it, {moreno.muffatto, francesco.ferrati}@unipd.it

**Abstract.** In the circular economy, companies design their business models based on the principles of the circular economy and try to identify new opportunities for value creation. Research on the circular economy business model (CEBM) is in its infancy: the terminologies used in the classification and the meanings and relationships between circular practices are unclear. In addition, very few studies examine the value analysis in each business model archetype of a circular economy. This study aims to categorize archetypes of business models for a circular economy and present the value analysis of each archetype from the literature. With the help of an integrated framework by ( Accenture.: Circular advantage innovative business models technologies value growth, 2014) and Van Renswoude (2015), we categorize 23 archetypes of business models for the circular economy into seven categories and analyze their value based on three dimensions value proposition, value creation, and delivery and value capture. Our results show that the product-service system models, product life extension models, and end-of-life resource recovery models are the most commonly discussed ones in the circular economy literature. Only a few articles discuss how value is created, delivered, and captured in each circular business model. Therefore, it is necessary to explore further the value delivery and value capture dimensions. Future studies could investigate the value analysis of business models for a circular economy from sector-specific perspectives.

**Keywords:** Circular economy · Circular business models · Circular economy business models · Value proposition · Value creation · Value delivery · Value capture

## 1 Introduction

In recent years, environmental degradation has escalated pressure to change production and consumption patterns, particularly among businesses to consider shifting their business models from linear to circular economies (Kirchherr et al., 2017). According to the EMF (2013), by designing superior materials, products, systems, and business


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 133–148, 2023.
https://doi.org/10.1007/978-981-19-9205-6_13

models, the circular economy (CE) seeks to eliminate waste by replacing end-of-life products with restoration, using renewable energy sources, and reducing toxic chemicals (EMF, 2013). The business model is one of the main themes and building blocks of circular economy thinking in which business model innovation takes a crucial part in the success of a circular economy (DeAngelis, 2018; Linder and Williander, 2017). Literature on circular economy with a business model perspective has become popular, sparking discussion between academicians and practitioners to understand the opportunities for creating, delivering, and capturing the value of a business while following the principle of the circular economy (Diaz Lopez et al., 2019; Lüdeke-Freund et al., 2018; Nußholz, 2018). Companies' business model transformation towards incorporating circular economy principles has a significant impact on the value creation, delivery, and capture (Bocken et al., 2016; Lüdeke-Freund et al., 2018; Planing, 2015). However, in the circular economy literature, few studies examine the value analysis in each business model for a circular economy (Okorie et al., 2021).

As a business model innovation tool, authors categorize business models for a circular economy from different perspectives. The most widely used framework of EMF (2015) and the updated versions by Van Renswoude et al. (2015), Lewandowski (2016), and Rosa et al. (2019) try to show the classification from the sources of value creation. While Accenture (2014), BSI (2017), R2π (2019), and Moreno et al. (2016) try to classify business models for circular economy according to their role within the CE and show the product outcome of such a business model. Classifications of business models in the circular economy lack unified terminologies (Lüdeke-Freund et al., 2018; Nußholz, 2017) and show ambiguity in the meaning and relationships between circular strategies (Blomsma et al., 2019). Existing classifications of business models for the circular economy do not present explicit criteria and scientific procedures (Nußholz, 2017; Pieroni et al., 2020). Our study uses circular business model classification frameworks by Accenture (2014) and Van Renswoude et al. (2015) to study the most discussed circular economy business model archetypes in the literature and develop a categorization to bridge the gap. By reviewing the literature, this study attempts to categorize existing business models for a circular economy and present the value proposition, value creation and delivery and value capture in each CEBM archetype. Section 2 presents the literature review on circular business model classifications and value analysis, followed by a methodological discussion of how the study was drafted and carried out (Sect. 3). We present the results of our research in Sect. 4, followed by conclusions in Sect. 5.

## 2 Theoretical Background

### 2.1 Value in Business Models for the Circular Economy

The business model for a circular economy (called a circular business model) is mostly defined based on the traditional business model definition of Osterwalder and Pigneur (2010) as well as Richardson (2008). Authors from the circular economy literature (for example. Manninen et al. (2018), Lüdeke-Freund et al. (2018), Zucchella and Previtali (2019)) define circular business models (CBM) by incorporating circular economy principles into the traditional business model. Circular practices can contribute to the creation and capture of value. However, the business model frameworks lack mechanisms to show which circular practices can capture what type of value. Few studies such as Bocken et al. (2016) and Lüdeke-Freund et al. (2018) analyze the value analysis of some circular business models. In order to integrate the sustainability and circularity evaluation of a business model and its sustainability impact at an ecosystem level, Antikainen and Valkokari (2016) try to redefine the business model canvas in light of the circular economy and sustainability concept. While Nußholz (2017) integrates circular strategies into the business model canvas. Highlighting the value creation aspects of circular business models, Linder and Williander (2017) and Lahti et al. (2018) relate the circular economy to the core components of a business model based on Richardson (2008). Table 1 summarizes few articles analyzing value in the business model of a circular economy.

In the traditional business model, authors (e.g. Richardson 2008; Osterwalder and Pigneur 2010; Frankenberger et al. 2013; Abell 1980) describe the business model components in different ways. As shown in Fig. 1 below, this study will adopt the three core components of a business model stated by Richardson (2008) to present the value analysis of each business model in circular economy.

### 2.2 Classification of Business Models for Circular Economy

Researchers and practitioners have explored and categorized circular economy business models from different perspectives. Studies on circular economy business models have used different classification frameworks developed by practitioners (international organizations and consulting firms) as one form of business model innovation tool in the literature. The most commonly used classification approaches are the ReSOLVE framework (EMF, 2015), CBM framework (Accenture, 2014), CBM strategies (Bocken et al., 2016), business models for CE (BSI, 2017), business models archetypes for a CE (Forum For the Future, 2018) and CBM scan (Van Renswoude et al., 2015). Following the ReSOLVE framework of (EMF, 2015), the updated work of Van Renswoude et al. (2015), Lewandowski (2016), and Rosa et al. (2019) seek to show classifications circular of business models from sources of value creation. The categorization of circular business models made Accenture (2014), BSI (2017), R2π (2019), and Moreno et al. (2016) focuses on classifying business models according to their role within the circular economy and showing the product outcome of such a business model. In Table 2, we make a comparison of the four classification approaches by Accenture (2014), BSI (2017), R2π (2019), and Van Renswoude et al. (2015).

Each classification approach fell to discuss one or more components in their classification. For example, Accenture's framework lacks two main categories: shifting physical products to virtual and resource-efficient practices before and after production. Among the many sub-business models for the circular economy under the product life extension model, hybrid models, gap-exploiter models, product modularity, and encourage sufficiency are the most discussed ones (Ceptureanu et al., 2018; Lewandowski, 2016; Nußholz, 2017; Pieroni et al., 2020; Planing, 2018) however, Accenture (2014) does not discuss these aspects.

Furthermore, Accenture (2014) discusses the resource recovery model in a more general way which does not emphasize circular practices such as industrial symbiosis

**Table 1.** Value considerations in the business models for circular economy literature

| Author(s) | Document Title | Business Models for CE | Business models dimensions | Focus |
|---|---|---|---|---|
| Lewandowski (2016) | Designing the Business Models for Circular Economy Towards the Conceptual Framework | Regenerate Share Optimize Loop, Virtualize Exchange (26 sub models) | Value propositions | Ownership-based; access to the product; or a pure service and offer incentives |
| | | | Channels | Sell and deliver virtualized value proposition virtually, and via virtual channels |
| | | | Customer relationships | Producing on-order, customer engagement, and social marketing strategies |
| | | | Revenue streams | Revenue generated from products, components, and raw materials collected back |
| | | | Key resources | Input choices (circular sourcing), less harmful materials to the environment, and virtualization of materials |

(*continued*)

(Guzzo et al., 2019; Lüdeke-Freund et al., 2018; Marke et al., 2020; Nußholz, 2017; Pieroni et al., 2020; Rosa et al., 2019), incentivized return & reuse (BSI, 2017; Husain et al., 2021; Lewandowski, 2016), collection of used products (Brendzel-Skowera, 2021; Hofmann, 2019; Pieroni et al., 2020), and energy recovery (Lewandowski 2016; Ceptureanu et al., 2019; Guzzo et al. 2019). Because of the noted gaps, Van Renswoude et al. (2015) and BSI (2017) updated the Accenture framework. The British Standard Institute (BSI, 2017) offers potential business models in six categories that are compatible with a circular economy. However, business models toward circular inputs (industrial symbiosis, renewable energy, bio-based and recyclable resources) are not part of the framework. Based on the four sources of value creation cycles (EMF 2015) and two added categories (dematerialized service and produce on-demand), Van Renswoude (2015) classifies circular economy business models into six categories and 19 sub-models. In

**Table 1.** (*continued*)

| Author(s) | Document Title | Business Models for CE | Business models dimensions | Focus |
|---|---|---|---|---|
| Bocken et al. (2016) | Product design and business model strategies for a circular economy | Business model strategies for slowing and closing resource loop | Value proposition | Performance and access to a service, affordable product by exploiting residual value), high quality and long-lasting product, and reduction in operating cost and risks |
| | | | Value creation & delivery | Service and maintenance, take-back systems and collaborations, design for durability |
| | | | Value capture | Extended use of the product, reduced material costs, premium pricing, and waste to value |
| Geissdoerfer et al. (2020) | Circular business models: A review | Cycling Extending Intensifying Dematerializing | Value proposition | Products/services, customer segments/markets; customer needs/problems; how to address them? |
| | | | Value Creation and Delivery | Key-value chain elements, core competencies, and resources capabilities |
| | | | Value capture | Revenue streams; cost drivers, revenue model |

this two frameworks, the shifting of physical products to a virtual model may include dematerialized services (Virtualize) and the narrowing resource loop model (optimization) may contain sub-models, such as made to order, waste reduction, and efficiency (BSI, 2017; Ceptureanu et al., 2018; EMF, 2015; Horvath et al., 2019; Manninen et al.,

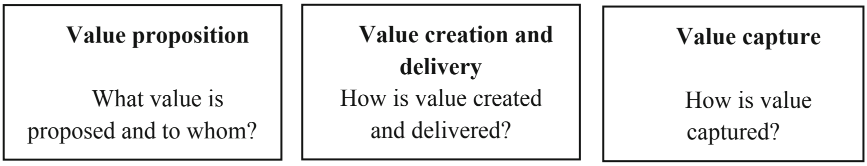



**Fig. 1.** Business model dimensions based on Richardson 2008

**Table 2.** CEBM categorizations (Van Renswoude 2015; Accenture 2014; BSI 2017; R2π 2018)

| Van Renswoude (2015) | | Accenture (2014) | BSI (2017) | R2π (2018) |
|---|---|---|---|---|
| Long cycle | Pure circles | Circular Supplychain | – | Circular sourcing Co-product recovery |
| | Cascades | Resource recovery | Recovery of secondary raw materials/by-products | Resource recovery |
| | Short cycle | Sharing platforms | Sharing economy/ platforms and collaborative consumption | – |
| | | Product as a service | Product as a service/product–service systems (PSS) | Access Performance |
| | | Product life extension | Product life cycle extension/reuse | Re-make Re-condition |
| Dematerialized services | | – | Dematerialization | – |
| Produce On demand | | – | On Demand | – |

2018; Marke et al., 2020; Rosa et al., 2019; Van Renswoude et al., 2015). To make a more comprehensive categorization of circular economy business model archetypes, this study uses an integrated framework adapted from Accenture (2014) and Van Renswoude (2015) and categorize 23 CEBMs into seven categories.

## 3 Methodology

We conduct a systematic literature review on academic and grey literature to explore and categorize existing business models in the circular economy and analyze the value in each circular business model. Using academic search engines Scopus and Web of Science, we identified relevant and adequate studies on circular business models using the keywords business model, circular economy, closed-loop, resource efficiency, and business strategy. Keywords were derived from prominent authors and keyword analysis software (Vosviewer) to support our analysis. The study excludes terms such as sustainability and sustainable development to limit the study only to a circular economy. Document types journal articles, reviews, and grey literature written in English and focusing on both circular economy and business model or discussing the circular business model as the major topic of the study are included. We reviewed 76 academic articles and six grey literatures to identify the most frequently discussed archetypes of business models for a circular economy based on descriptions, examples, similarities in the terminologies, and the frequency of use in the literature and categorize them and analyze value (Fig. 2).

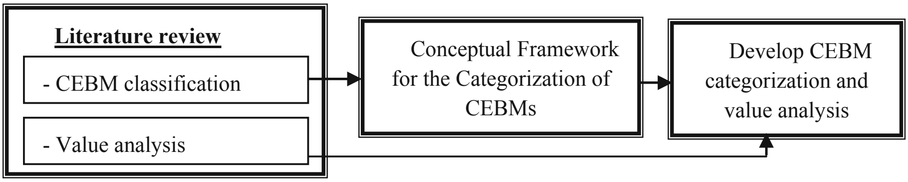



**Fig. 2.** Methodology to develop CEBM categorization and value analysis

In this study, we develop a circular economy business model categorization by using the Accenture (2014) and Van Renswoude (2015) framework in an integrated way (Fig. 2). Accenture (2014) presents five distinct types of CBMs and 11 sub-models: (a) circular supply chain that is based on renewable energy, bio-based, or recyclable materials and the "built to last" approach; (b) sharing platforms that encourage collaborative usage, access, or ownership models (c) the product as a service model provides access to products or performance while maintaining product ownership; (d) the product life extension model refers to extending the life cycle of a product through repairs, maintenance, upgrades, resale, and re-manufacturing; (e) the resource recovery model deals with recovering energy or resources from wastes or by-products (Accenture, 2014).

The CBM Scan (Van Renswoude et al., 2015) classifies BMs into six cycles and 19 CBMs based on the value flow. The cycles and related CBMs include: (i) a short cycle includes the CBMs paying per service, repairing, reduction of waste, sharing platform, and progressive purchase; (ii) a long cycle includes the performance-based contracts, the take-back system, resale, and refurbishment models; (iii) a pure circle includes the CBMs cradle-to-cradle and circular sourcing models; (iv) cascading categorized with upcycling, recycling and collaborative production BMs; (v) dematerialized services contain the shifting of physical products to virtual and rental models on subscription bases; and (vi) produce on-demand includes produce on order, 3D printing, and customer voting (Van Renswoude et al., 2015). While this classification includes most CBMs, the models related to extending a product's life cycle, such as modular design, upgrading, hybrid, or gap exploiter models, are missing. The 3D printing and take-back management do not reflect a complete business model since they are production methods and enabling mechanisms. By reviewing the literature on the circular economy business model, we develop a conceptual framework (Fig. 3) for categorizing the business models in the circular economy.

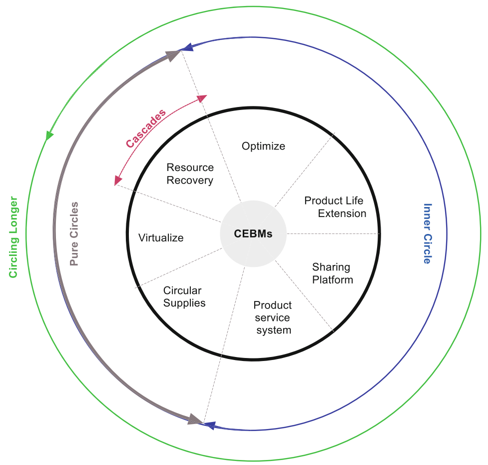



**Fig.3.** A conceptual framework for categorizing business models for a circular economy based on Accenture (2014) and Van Renswoude (2015)

# 4 Result

## 4.1 Circular Economy Business Model Archetypes

This study reviews the scholarly research and grey literature to analyze and categorize business model archetypes for the circular economy with the framework developed in Sect. 3. We categorize business models for a circular economy using the Accenture (2014) framework and the Van Renswoude (2015) framework in an integrated way as shown in Fig. 3. In addition to the five main categories of Accenture, we adopt two other groups from Van Renswoude (2015). This study identifies the sub-models from the reviewed literature made on seventy-six academic articles and six grey literatures. As shown in Fig. 4 below, this study identifies seven categories and twenty-three subcategories of business models for circular economies.

- Circular Supplies focuses on inputs materials that are renewable, bio-based, or recyclable, helping to replace single-lifecycle inputs (Accenture, 2014). The sub-models we have included in our categorization are bio-/secondary materials; industrial symbiosis; classic long-life model; modular design; design for x; and renewable energy.
- Optimize model efforts to improve the performance or efficiency of products and reduce waste in manufacturing processes and supply chains (EMF, 2015). Produce on-demand and resource efficiency sub-models are included in this categorization.
- A product-service system provides access to products or performance while maintaining product ownership (Accenture, 2014). The sub-models we have included in our categorization are the access model, performance model, and product-oriented.
- Sharing platforms encourage the sharing or pooling of under-utilized products through shared use, access, or ownership (Accenture, 2014).
- Virtualize (dematerialized services) focuses on delivering products virtually than physically (EMF, 2015).

- Product Life Extension focuses on extending the life of products/components (Accenture, 2014). Sub-models included in our categorization are repair and maintenance, reusing/redistributing, encourage sufficiency, upgrading, hybrid model, gap-exploiter model, and re-manufacturing/refurbishing.
- The resource recovery model focuses on recovering energy or resources from wastes or by-products (Accenture, 2014). We have included sub-models: recycling, incentivized return, energy recovery, and collection and take-back of used products in our categorization.

This study highlights that most studies in the circular economy business model literature concentrate on the product-service system models, product life extension models, and end-of-life resource recovery models (Fig. 5).

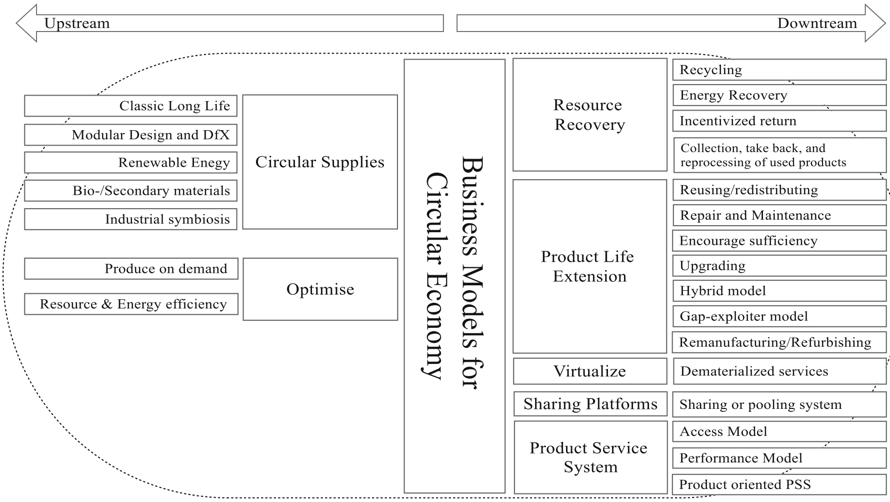



**Fig. 4.** Archetypes of business models for circular economy

## 4.2 Circular Economy Business Model Value Analysis

Discussions made in Sect. 2.1 show that literature on the circular economy business model addresses value in various considerations. By reviewing the academic papers and grey literature, this study summarizes the value creation and delivery process, the propositions, and value capture of business models in the circular economy as shown in the table below (Table 3) using Richardson's (2008) business model framework.

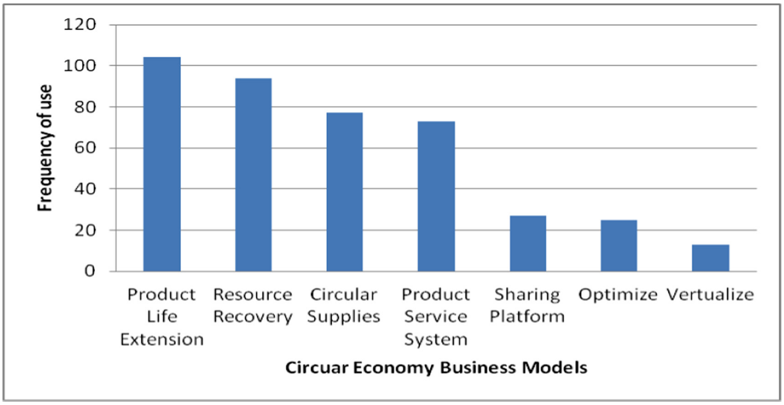



**Fig. 5.** Most investigated business models in the circular economy literature

**Table 3.** Value analysis of business models in the circular economy

| Archetype | Value proposition | Value creation and delivery | Value capture |
|---|---|---|---|
| Bio-/secondary materials | Environmentally sustainable material usage (recycled, renewable, recyclable, or biodegradable) | Value is created using designing products to use waste as input and circular products or materials (recycled and renewable; recyclable, or biodegradable) | Value can be captured through premium prices for environmentally sustainable products. Cost can be related to reduction of waste disposal and inefficiencies costs |
| Classic long-life model | Provide high-quality and long-lasting (durable) products | Value is created through designing products that last for a long time or durable products | Value is captured through price premium for longevity and high quality of products Cost related to long-term service and product warranty cost |
| Renewable energy | Manufacturing and functioning with renewable energy | Value is created with the use of renewable energy as source to produce and process | Information not available |

(*continued*)

**Table 3.** (*continued*)

| | | | |
|---|---|---|---|
| Modular design & design for x | Modular products with ease of reparability and design for (recycling, remanufacturing and reuse, disassembly, and environment) | Create value by designing products into smaller parts that can be used and replaced (repaired, maintained, disassembled, re-manufactured, recycled, etc.) easily | Information not available |
| Industrial symbiosi*s* | Residues or by-products of one process as production input for another process; reduction in overall operating cost; supply risk reduction; elimination of third-party waste and synergistic partnerships | Create value from residual resource streams, collaborative agreements to share communal services, and exchanging by-products of materials, energy, and water | Value is captured through joint cost reductions and repurposing of previous waste streams to a new business line |
| Produce on-demand | Provide products or services only when demanded, with zero stocks | Value is created by producing products or services only when demanded | Value is captured through material and energy cost reduction |
| Resource and energy efficiency | Information not available | Value is created by waste reduction activities and minimizing energy consumption both in the production process and before | Value is captured through the reduction of waste and minimizing energy consumption |
| Collection and take-back of used products | Facilitate return or collection of used products or components | Value is created by taking-back used products (as well as packaging) from distributors and end-users, leading to closing material loops | Value is captured through potential new revenues or savings from the reduction of energy and material costs |

(*continued*)

**Table 3.** (*continued*)

| | | | |
|---|---|---|---|
| Access model | The convenience of on-demand availability; flexibility and greater range of choice | Value is created by delivering customer service and related asset management (maintenance, repair, and control of the product) without transferring the product physically | Value is captured through recurring service<br>Cost related to maintenance and asset management cost |
| Performance model | Product functionality; result; user education to shift from owning to using; product maintenance, repair and, control | Value is created by delivering functionality/result rather than ownership and activities may include maintenance, repair, upgrade, diagnostics, and performance reporting | Value is captured through recurring service<br>Cost related to maintenance and asset management cost |
| Product-oriented PSS | Provide information and assistance to customers about product safety, use, maintenance, and repair | Value is created through product-related training, advice, and consultancy services | Value is captured through extended product warranties or take-back agreements |
| Sharing or pooling systems/platforms | Provide the ability to share the use, access, or ownership of products between members of the public or between businesses, and maximize the utilization of products | Value is created by matching owners and users of overcapacities shared with some form of transactional arrangement for commercial purposes | Value captured from the sharing of products, assets or Services |
| Dematerialized service | Provide product and service functionality virtually or digitally | Value is created and delivered by replacing physical infrastructure/assets, services, or processes with digital/virtual services | Value is captured with recurrent income from service contracts/ subscriptions |

(*continued*)

**Table 3.** (*continued*)

| | | | |
|---|---|---|---|
| Repair and maintenance | Extending product lifecycle through maintenance and repair services as well as providing repaired (second hand) products with an affordable price | Value is created by repairing and maintenance activities such as failure prediction, detecting and replacing defective or worn-out parts as well as remarketing and reselling repaired equipment | Value captured from sale of repaired products |
| Encourage sufficiency | Encourage and educate consumers to reduce consumption; provide warranties; upgrading | Value is created by designing long-lasting products; repairing, upgrading, remanufacturing, or remarketing products Value delivered by conscious actions to moderate sales activities | Value is captured with a potential reduction in the need to produce physical goods and premium pricing |
| Upgrading | Provide upgraded product | Value is created by replacing outdated modules or components with superior ones | Value captured from the sale of upgraded products. Material cost reduced relative to the original manufacturing |
| Hybrid model | Provide durable products in combination with short-lived consumables to be replaced | Value is created by designing a product with a combination of durable products and short-lived consumables | Value captured from the gap in a lifetime of components |
| Gap-exploiter model | Provide a service of exploiting a product's residual value | Value is created by exploiting lifetime value gaps in a company's products or services | Value captured from the gap in a lifetime of products or services |

(*continued*)

**Table 3.** (*continued*)

| | | | |
|---|---|---|---|
| Remanufacturing/Refurbishing | Remanufactured products (like new) with an affordable price | Value is created by remanufacturing or refurbishing activities | Value captured from the sale of remanufactured products. Material cost reduced relative to the original manufacturing |
| Reusing/Redistributing | Second and third-hand products with an affordable price | Value is created by reselling to the second and third-hand market or reusing them with or without repairs or upgrades | Value is captured by redistributing second and third-hand products |
| Recycling | Environmental sustainability of recovered materials | Value is created by Upcycling or downcycling of products or materials at the end of life | Value captured from the sale of recovered materials; reduction of waste disposal cost |
| Incentivized return | Incentive customers to return used products for a predetermined value | Value is created by incentivizing customers to return used products at a predetermined value for enabling products to have the next life | Value is captured by reselling products to earn additional income. Cost related to maintenance and refurbishment |
| Energy recovery | Provide energy recovered from waste | Value is created by recovering energy out of waste materials | Value captured from the sale of energy from waste; reduction of waste disposal cost |

## 5 Discussion and Conclusion

This study conducts a literature review on circular economy business models to explore classification and analyze their value. Since circular economy business model research is still in its infancy, very few studies examine the value analysis in business models for a circular economy and there is also a lack of unified understanding and categorizations. In most of the reviewed articles, the categorization of business model archetypes for the circular economy does not show explicit criteria and detailed methodologies to explore and systematize the circular strategies. Seventy-six academic articles and six grey literatures were reviewed to identify the 23 most frequently discussed archetypes of business models for a circular economy based on descriptions, examples, similarities in the terminologies, and the frequency of use in the literature and categorize them into seven categories using an integrated framework of Accenture (2014) and Van Renswoude (2015). The categories include the circular supplies model, product life extension model, optimize model, Virtualize model, product-service system model, and resource recovery model. These results offer valuable insights into the current understanding of BMs for circular economies. This study highlights that most studies in the circular economy business model literature concentrate on the product-service system models, product life extension models, and end-of-life resource recovery models. Regarding the value analysis, we analyzed the value based on the business model dimensions: value proposition, value creation and delivery, and value capture. Only a few articles discuss how value is created, delivered, and captured through each circular business model. Therefore, this study contributes in clarifying how value is proposed, created, and captured in the context of a circular economy. Based on the findings, it is necessary to further explore the value delivery and value capture dimensions. Studies in the future may examine the value of business models for a circular economy from the perspective of different sectors.

## References


Accenture.: Circular advantage innovative business models technologies value growth (2014)

Antikainen, M., Valkokari, K.: A Framework for sustainable circular business model innovation. Technol. Innov. Manag. Rev. **6**(7) (2016)

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**(5), 308–320 (2016). https://doi.org/10.1080/21681015.2016.1172124

Brendzel-Skowera, K. Circular economy business models in the SME sector. Sustainability **13**(13) (2021). https://doi.org/10.3390/su13137059

BSI.: Framework for implementing the principles of the circular economy (2017)

Ceptureanu, S.-I., Ceptureanu, E.-G., Murswieck, R.G.D.: Perceptions of circular business models in SMEs. www.amfiteatrueconomic.ro **20**(48) (2018). https://doi.org/10.24818/ea/2018/48/310

DeAngelis, R.: Business models in the circular economy concepts, examples and theory by Roberta De Angelis (auth.) (z-lib.org).pdf (2018)

Diaz Lopez, F.J., Bastein, T., Tukker, A.: Business model innovation for resource-efficiency, circularity and cleaner production: what 143 cases tell us. Ecol. Econ. *155*, 20-35 (2019). https://doi.org/10.1016/j.ecolecon.2018.03.009

EMF.: Towards a circular economy: economic and business rational for an accelerated transition (2015)

Guzzo, D., Trevisan, A.H., Echeveste, M., Costa, J.M.H.: Circular innovation framework: verifying conceptual to practical decisions in sustainability-oriented product-service system cases. Sustainability **11**(12) (2019) https://doi.org/10.3390/su11123248

Hofmann, F.: Circular business models: business approach as driver or obstructer of sustainability transitions? J. Clean. Prod. **224**, 361–374 (2019). https://doi.org/10.1016/j.jclepro.2019.03.115

Horvath, B., Khazami, N., Ymeri, P., Fogarassy, C.: Investigating the current business model innovation trends in the biotechnology industry. J. Bus. Econ. Manag. **20**(1), 63–85 (2019). https://doi.org/10.3846/jbem.2019.6880

Husain, Z., Maqbool, A., Haleem, A., Pathak, R.D., Samson, D.: Analyzing the business models for circular economy implementation: a fuzzy TOPSIS approach. Oper. Manag. Res. **14**(3–4), 256–271 (2021). https://doi.org/10.1007/s12063-021-00197-w

Lahti, T., Wincent, J., Parida, V.: A definition and theoretical review of the circular economy, value creation, and sustainable business models: where are we now and where should research move in the future? Sustainability **10**(8) (2018). https://doi.org/10.3390/su10082799

Lewandowski, M. (2016). Designing the Business Models for Circular Economy—Towards the Conceptual Framework. *Sustainability, 8*(1) doi:https://doi.org/10.3390/su8010043

Linder, M., Williander, M.: Circular Business Model Innovation: Inherent Uncertainties. Bus. Strateg. Environ. **26**(2), 182–196 (2017). https://doi.org/10.1002/bse.1906

Lüdeke-Freund, F., Gold, S., Bocken, N.M.P.: A review and typology of circular economy business model patterns. J. Ind. Ecol. **23**(1), 36–61 (2018). https://doi.org/10.1111/jiec.12763

Manninen, K., Koskela, S., Antikainen, R., Bocken, N., Dahlbo, H., & Aminoff, A.: Do circular economy business models cap...nded environmental value propositions (2018)

Marke, A., Chan, C., Taskin, G., Hacking, T.: Reducing e-waste in China's mobile electronics industry: the application of the innovative circular business models. Asian Educ. Dev. Stud. **9**(4), 591–610 (2020). https://doi.org/10.1108/aeds-03-2019-0052

Moreno, M., De los Rios, C., Rowe, Z., Charnley, F.: A conceptual framework for circular design. Sustainability **8**(9) (2016). https://doi.org/10.3390/su8090937

Nußholz.: Circular business models: defining a concept and framing an emerging research field. Sustainability **9**(10) (2017). https://doi.org/10.3390/su9101810

Nußholz.: A circular business model mapping tool for creating value from prolonged product lifetime and closed material loops. J. Clean. Prod. (2018). https://doi.org/10.3233/978-1-61499-820-4-309

Okorie, O., Charnley, F., Russel, J., AshutoshTiwari, Moreno, M.: Circular business models in high value manufacturing Five industry cases to bridge theory.pdf (2021)

Osterwalder, A., Pigneur, Y.: Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers. Wiley (2010)

Pieroni, M.P.P., McAloone, T.C., Pigosso, D.C.A.: From theory to practice: systematising and testing business model archetypes for circular economy. Resour. Conserv. Recycl.**162** (2020). https://doi.org/10.1016/j.resconrec.2020.105029

Planing, P.: Towards a circular economy—how business model innovation will help to make the shift. Int. J. Bus. Glob. **20**(1) (2018) https://doi.org/10.1504/ijbg.2018.10009522

R2π, P.: Circular Business Model Innovation Toolkit (2019)

Richardson, J.: The business model: an integrative framework for strategy execution. Strateg. Chang. **17**(5–6), 133–144 (2008). https://doi.org/10.1002/jsc.821

Rosa, P., Sassanelli, C., Terzi, S.: Towards circular business models: a systematic literature review on classification frameworks and archetypes. J. Clean. Prod. **236** (2019). https://doi.org/10.1016/j.jclepro.2019.117696

Van Renswoude, K., Wolde, A.T., Joustra, D.J.: Circular Business Models—Part 1: An introduction to IMSA's circular business model scan (2015)

Zucchella, A., Previtali, P.: Circular business models for sustainable development: a "waste is food" restorative ecosystem. Bus. Strateg. Environ. **28**(2), 274–285 (2019). https://doi.org/10.1002/bse.2216

# Circular Economy Models in the Construction Sector: A Plastics Recycling Use Case

Anthony Soroka[1](✉), Michael Robinson[2], Jonathan Gosling[1], Lucy Hoggins[3], Jane Hall[4], and Mohamed M. Naim[1]

[1] Cardiff Business School, Cardiff University, Cardiff CF10 3EU, UK
{SorokaAJ,GoslingJ,NaimMM}@cardiff.ac.uk
[2] Cardiff School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
RobinsonM12@cardiff.ac.uk
[3] Resilience Sustainable Solutions, Cardiff, UK
lucy@resiliencesustainability.co.uk
[4] Green Edge Applications, Cardiff, UK

**Abstract.** There is global desire to reduce virgin plastic use and enhance the collection and exploitation of plastics waste. Hence, governments are setting high targets for plastics recycling and using statutory instruments such as the plastic packaging tax as well as offering support to the manufacturing sector to trial increasing use of recycled plastic to stimulate end markets with the aim of reducing the amount of virgin production. The construction sector has much promise in terms of adopting circular economy principles and here we report on the results of a trial project to introduce a closed-loop supply chain model. More specifically, we seek to develop appropriate circular economy business models that manufacturers to the construction sector may adopt to enhance plastics recycling. We identify three potential circular economy models: (1) customers return direct to manufacturer, (2) customers return direct to 3rd party processor, (3) customers return to hubs, with the second chosen for trialling. Several barriers were identified, which have been categorised according to demand (perception of quality), supply (limited specialist suppliers, the provenance of the returned plastic, sourcing quality and consistent recycled material), organizational (internal policies and decision-making factors) and control (concrete contamination of end-of-life plastic products, and a lack of cost incentives). Provisional results from in-situ trials of the recycled content tubs suggest that a circular economy approach is feasible.

**Keywords:** Reverse logistics · Customer perceptions · Closed-loop supply chain

## 1 Introduction

There is global desire to reduce virgin plastic use and enhance the collection and exploitation of plastics waste. This is driven by the sheer volume of plastic that is produced annually, estimates vary but it has been suggested that around 370 million tonnes of plastic are produced globally each year [1]. This accounts for 4–8% of the world's oil production [2].


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 149–158, 2023.
https://doi.org/10.1007/978-981-19-9205-6_14

Some 95% of plastic packaging material in terms of value, $80–120 billion, is lost annually, with 32% of plastic packaging escaping collection systems and only 2% being used with closed-loop systems for same or similar quality applications [2]. Even the most advanced economies in the world generate significant volumes of plastic waste, for example, the EU generates 26 million tonnes of plastic each year, with less than 30% being recycled, and some 70% going to landfills or incinerators [3].

Hence, governments are setting high targets for plastics recycling and targets for incorporation of recycled content into single use items to stimulate market demand for recycled plastic, reducing the amount of virgin production. Due to these laws, social pressures, environmental concerns, and potential economic savings companies are considering the collection and recycling of their 'end-of-life' products as well as the tradition manufacture of new products. As a result, traditional supply chains are becoming more closed loop.

The construction sector has much promise in terms of adopting circular economy principles, but has significant barriers and complexities in successfully adopting practices [4–6]. Hence, we report on the results of a trial project to introduce a closed-loop supply chain model.

Specifically, we seek to answer the research question - "what circular economy business models may manufacturers supplying the construction sector adopt along the supply chain in order to enhance plastics recycling?"

## 2 Background

### 2.1 Circular Economy

The circular economy, although it has received considerable interest recently, is not a new concept. In 1976 Stahel and Ready, in a report to the Commission of the European Communities, presented the concept of a 'loop economy' to describe industrial strategies for resource efficiency, waste prevention, job creation, and dematerialisation of manufacturing [7]. Furthermore, Stahel in 1982 [8] began to detail the concept of what we call today 'products as a service', in other words selling product use as opposed to ownership of goods, can help deliver what is called today the circular economy, allowing industries to profit and reduce the risks associated with post-consumer waste.

More recently the circular economy concept definition widely adopted is that given by the Ellen MacArthur Foundation, namely that the Circular Economy (CE) is "an industrial economy that is restorative or regenerative by intention and design" [9].

Stahel in more recent work [10] categorized CE business models into two broad groups. The first is those concerned with the reuse and life extension (repairing, remanufacturing, and upgrades). The second is those obtaining new resources from what is often called post-consumer waste via recycling their materials. The focus of this study is the latter.

While there is acknowledgement of the huge potential impact of adopting circular economy principles in the construction industry, the research knowledge base has been slow to adapt principles for a construction context [4]. There is no broad consensus of what the circular economy 'looks like' in the built environment and the behavioural incentives are not yet effective in driving change [4].

### 2.2 Closed-Loop and Circular Supply Chains

In a traditional forward supply chain, material flow is considered to be unidirectional. Going from material (raw or component) suppliers to the manufacturers, and eventually to the consumers. However, in closed-loop supply chains (CLSC) there are reverse-direction flows of used/end-of-life products back upstream in the supply chain.

There are two primary drivers for the adoption of CLSC by industry: legislative pressure and economic benefit [11]. Despite this drive towards the adoption of more circular supply chains the uncertainties related to being able to procure used products/parts of the appropriate cost, quality, and quantity, together with customer attitudes are still the main barriers to achieving profitability [12, 13].

Studies have shown that technological developments can enable post-consumer product returns to be handled effectively and in an economically beneficial manner [14]. Recent research on sourcing of the required post-consumer products has suggested that there is a need to develop strategic long-term commitments between a group of core actors to develop the systems and networks, including the creation of potentially new relationships [15].

Although CLSCs are at the core of the CE it is considered that they have been mainly treated as two separate themes of research [16]. This work will link the two through an industrial use-case of creating a CLSC for mortar tubs.

Batista et al. [17] develop fundamental aspects of a circular supply chain, based incorporating the closed loop supply chain concept, incorporating sustainability augmented design complexity, downstream design and value chain composition.

In the construction sector, there is growing awareness of the need for circular practices supported by the move towards measurement of embodied carbon impact of construction and buildings, and many organisations are adopting lifecycle approaches to projects that help to support circular practices, but logistics networks, business models and appropriate incentives remain key barriers to effective adoption [5, 6].

## 3 Research Method

The company at the centre of this use case supplies the construction sector with plastic products manufactured using a rotational moulding process, a process ideally suited to large, low production volume items. The process uses pulverised polyethylene (PE) or low-density polyethylene (LDPE) powder, ground to a diameter of $<600\ \mu m$. The powder is poured into metal moulds and rotated in a gas fired oven to layer the inside of the mould resulting in a shaped product. The process lends itself to production of bespoke shaped products, for example, fuel tanks, buoys and our focus product, mortar tubs for the construction industry. Currently, the company manufactures around 25,000 mortar tubs per year used to transport mortar around building sites, mostly on forklift trucks, but also in lift products. These products are mainly made from virgin PE. This is bought in a natural colour and a powder colour pigment added if customers require a coloured product. Currently some recycled content is used, sourced from off-cuts from their process is granulated in house then shipped to another company be extruded with a black colour masterbatch and pulverised into a powder.

The aim of this work is to increase the amount of recycled content in the mortar tub product. It is estimated that if the recycled content is increased by 75–80% in the mortar tub range, it will require around 220 tonnes of recycled material per annum, hence, stimulating the market for recycled materials. Furthermore, it can demonstrate that recycled materials can be used to manufacture a highly robust product.

We adopt a problem solving, interdisciplinary, design science approach working collaboratively with a manufacturer of plastic products used in construction as a high volume, mostly consumable product during the build phase. We take a systems wide perspective of the supply chain, taking due account of the product and processes, exploiting materials testing, process modelling, sales data analysis, and customer interviews to establish a descriptive model of the current state. One of three potential circular economy models is trialled to determine the outcomes of its application.

A team of academics and practitioners worked closely together on the trial project to develop the final solution. The team included environmental consultants, the managing director of a plastics manufacturer, academics from across business and engineering disciplines. An important outcome from the collaborative working across the project team was current state process map, and a future state process map that identifies different circular economy flows and solutions.

Data collection phase occurred via a number of stages. First, a survey of 10 of the largest customers was conducted with two key groups of customers. The first is Wholesalers, who generally buy in larger batches and then sell onto housebuilders or general builders. Tubs may be purchased as part of a range of engineering and bricklaying ancillary equipment. The second is Housebuilders, who purchase based on site requirements and send tubs directly to site e.g. in batches of 10. The survey was used to gain insights into barriers and incentives for circular economy models.

Once the circular economy routes, barriers and enabler were investigated, the next phase involved material testing and in-situ trials. The material testing involved (uniaxial tensile) and dynamic (Charpy impact) to assess brittle failure, material strength, and the effects of repeated recycling. The company's existing recycled offering (50% recycled) was compared against options consisting of varying levels of the new recycled material source to virgin material.

The trials involved the production of a sample of 80 mortar tubs from recycled materials, adhering a QR code with instructions for use onto each tub, and then efforts to track and monitor recycled tubs in use.

Under ideal circumstances the QR codes would be scanned at several points during its journey through the CLSC, and at least at the point of dispatch from production, when it is discarded and when it arrives at the recycling facility. Several methods beyond the use of QR codes were also employed to monitor and track the use of the mortar tubs which were released onto construction sites:

- Trial participants were contacted regularly to encourage use of the tracking technology and to seek feedback on the quality and suitability of the tubs.
- QRCode asset tracking software reporting data was reviewed to determine whether participants had used the software correctly and to check the location of the tubs ready for repatriation.

# 4 Development of a Circular Supply Chain Model

## 4.1 Existing Business Model

Figure 1 shows a high-level big picture illustration of the plastic tub supply chain with recycled inputs. It shows that there is both a conventional open-loop supply chain where virgin raw material is used to produce mortar tubs that contain no recycled content and one closed-loop flow, L1, where tubs are manufactured using recycled material. Currently offcuts and other waste from the production process are given to a recycling company that then processes the waste into powder that suitable for manufacturing.

Once a tub has been produced they are dispatched to several categories of customer; mortar companies that use the tubs to provide mortar, wholesalers that can supply either builders or smaller retailers, house building companies, and finally general builders including self-employed bricklayers. Once a builder has finished using a mortar tub it is unknown what happens to them, although interviews suggested that they go to landfill. A proportion of these would be unrecyclable. However, another proportion could re-enter the supply chain. Industrial participants were unable to supply data relating to the potential flows of re-usable materials, as indicated by the stock holding points in Fig. 1.

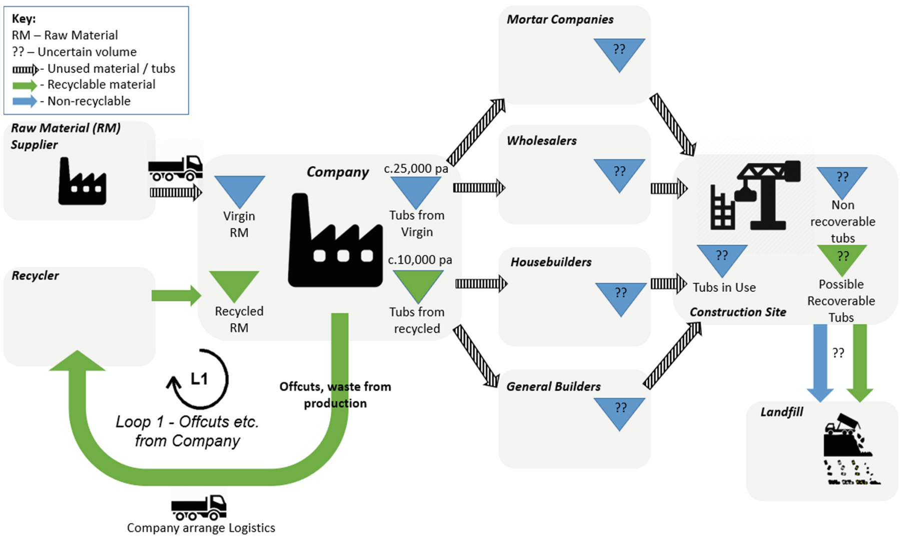



**Fig. 1.** Current plastic tub supply chain with existing recycled inputs

## 4.2 Circular Economy Challenges and Perception

The adoption of more circular approaches faces two challenges; the availability of recycling services and consistent material content, and customer perception of recycled products.

During the research it became apparent that there were very limited sources of data which provide information on specific plastic types produced by recyclers. Significant input was required to determine suitable potential sources of recycled polythene plastics for the rotational moulding process.

Focusing on the responses from housebuilders, we conclude the following:

- The purchasing approach is mostly unsystematic i.e. 'ad-hoc' for each site. There is some evidence of batching/batch sizes. Cost is the primary driver, and quality is a secondary driver.
- With respect to re-use from site to site, there is some evidence of re-use, but no specific data available for analysis.
- There are no clear indicators of how long tubs last. There are mixed approaches and enthusiasm towards segregation, and little appetite exists to clean tubs on site, using the existing business model.
- Space constraints, cleaning, logistics and incentives were all highlighted as issues and challenges to overcome, so will likely need to be considered for any proposed circular economy model.

### 4.3 Barriers

Based on the surveys of perceptions, a number of barriers were identified, which have been categorised according to demand, supply, organisational process, and control (as per [18]), as shown in Table 1.

**Table 1** Identified barriers to a CE approach

| Category | Potential barriers |
|---|---|
| Demand | Perception of quality |
| Supply | Limited specialist suppliers, the provenance of the returned plastic, sourcing quality and consistent recycled material |
| Organizational | Internal policies and decision-making factors |
| Control | Concrete contamination of end-of-life plastic products, and a lack of cost incentives |

### 4.4 Potential Circular Supply Chain

Figure 2 below shows a big picture of a future CE supply chain scenario. It is possible to see a number of recovery routes on the diagram.

Firstly, Route 1, there is customer re-use. There is some evidence that larger house-builders are doing this, transferring tubs to alternative sites after use, but little precise data on the number of tubs being recovered. Also, Route 2, the company could collect and process tubs direct from building sites. There is some positivity in the survey data regarding this route. However, barriers to logistics and cleaning, and incentivisation were raised. Then, Route 3, the company could collect and process via a wholesale return model, or, finally, Route 4, tubs could be returned to the company via waste management companies. These four routes constitute a potential new closed-loop L2.

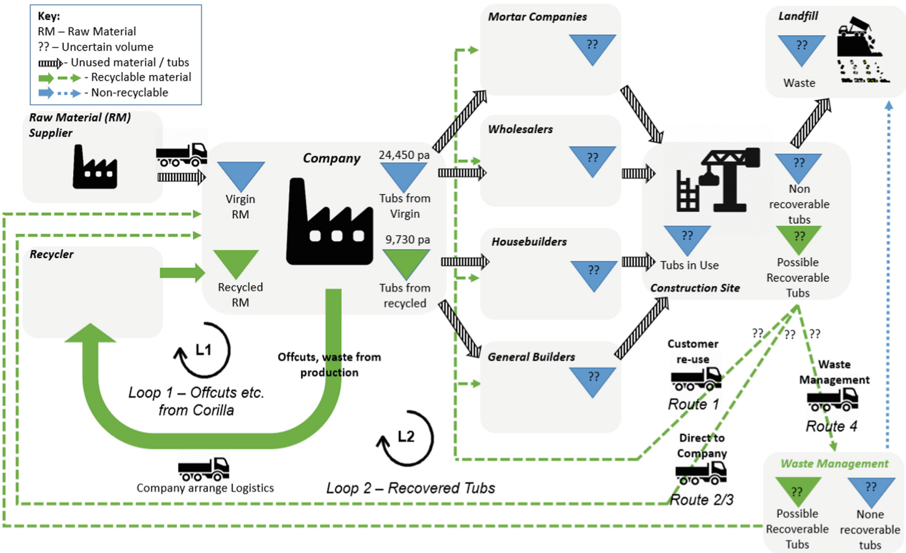



**Fig. 2** Proposed plastic tub supply chain with recovery routes

Within the survey, the perceptions of two further variants on the above routes were raised. These were the customer proactively arranging delivery back to the company and a leasing model. Indications from the survey suggested that this would be challenging as customers do not see the rewards as greater than the cost. This suggests that although from a CE perspective it might be the most appropriate approach [8] it could be difficult to achieve without customer buy-in.

The logistics provider of the company was also interviewed which revealed that a hub model is currently used, where all products are bulked and shipped to a hub in Leicester before being distributed across the country. Whilst this model may work for collections of waste tubs in the Midlands and North of Leicester, but it may be more cost effective and efficient for customers based in the South to employ a localised collection option.

## 5 Material Testing and In-situ Trials

The material testing involved quasistatic (uniaxial tensile) and dynamic (Charpy) tests to assess brittle failure, material strength, and the effects of repeated recycling. The laboratory-based material testing showed that differing levels of recycled material have a limited effect on quasistatic performance, when comparing results from virgin, 50%, 75% and 100% recycled content. More specifically it showed 70% higher impact energy for the 75% and 100% recycled content material options, compared to the 50% option (the company's existing recycled offering) - 28.4 and 27.4kJm$^2$ vs 16.3 kJm$^2$.

Informed by the material testing confirming the suitability of using recycled material, and based on the circular economy supply chain model illustrated in Fig. 2 three options were shortlisted for the trials:

1. customers return direct to manufacturer
2. customers return direct to 3rd party processor
3. customers return to hubs

In discussion with trial participants, the second option was chosen for trialling. The CE model developed is illustrated in a simplified form by Fig. 3 and this forms the basis of the in-situ trials. Critically, each tub would need to be tracked to ensure its location is known to aid repatriation, with instructions on how to return the tub to the recycling facility where it can be re-processed. Several waste tracking technologies were appraised including GPS trackers, QR codes, RFID Tags, PolyTag, manual tracking. Overall, it was concluded that the asset tracking technology best meets the needs of the in-situ trials.

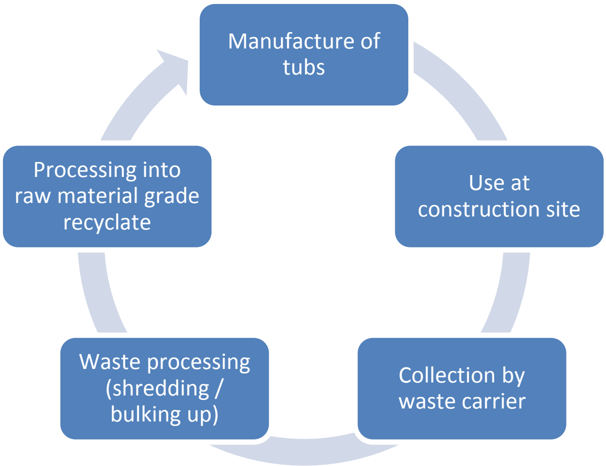



**Fig. 3.** Simplified CE model

Initial feedback from the test sites was positive, with no negative feedback regarding tub quality / durability received. Comments from the trial companies include: "Just as good as the ones we normally buy" (House Builder); "Holding up well especially through the frosty weekend, and performing as well as virgin" (Construction Materials). The design characteristics (colour and height) might need changing for particular customers due their corporate identity being associated with a particular colour. Finally some suggestions to test at temperatures below freezing were received, to address concerns associated with whether recycled being more susceptible than virgin to cracking.

## 6 Discussion and Conclusions

At the outset we asked, "what circular economy business models may manufacturers supplying the construction sector adopt along the supply chain in order to enhance plastics recycling?". To answer this, we report on the results of an applied pilot project, focusing on re-use and recycling of plastic mortar tubs, to introduce a closed-loop supply chain model. The project incorporated industry representatives, and an interdisciplinary team of researchers, to adopt a problem solving, design science approach to the development of a new model.

The findings from the pilot project identified three potential circular economy models: (1) customers return direct to manufacturer, (2) customers return direct to 3rd party processor, (3) customers return to hubs, with the second chosen for trialling. A number of barriers were identified, which have been categorised according to demand, supply, organisational process and control. Demand: perception of quality. Supply: limited specialist suppliers, the provenance of the returned plastic, sourcing quality and consistent recycled material. Organizational: internal policies and decision-making factors. Control: concrete contamination of end-of-life plastic products, and a lack of cost incentives.

The proposed circular economy business model builds upon Batista et al.'s fundamental aspects of a circular supply chain [17]. Through incorporating sustainability (the manufacturer already utilises by-product recycling), augmented design complexity (the models adopt restorative processes and manufacturing forward flows), downstream design (they encourage restorative processes with customers) and value chain composition (there are traditional and restorative supply chains with forward and reverse flows of virgin and recycled materials).

Results from material testing suggest that recycled material is unlikely to negatively influence performance, when benchmarked against virgin material. Provisional results from the in-situ trials indicate that a circular economy approach is feasible with no negative feedback regarding tub quality / durability received from the trial sites.

It is important to address the barriers early, and in consultation with key stakeholders. Potential supply barriers were addressed by finding a process to convert end-of-life tubs into a material which is comparable to virgin plastic. Demand barriers were challenged using demonstration trials to show that recycled products compared well with virgin plastic.

**Acknowledgements.** This work was led by WRAP Cymru with funding from Welsh Government.

## References

1. Kumar, R., Verma, A., Shome, A., Sinha, R., Sinha, S., Jha, P.K., Kumar, R., Kumar, P., Das, S., Sharma, P., Vara Prasad, P.V.: Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. Sustainability **13**, 9963 (2021). https://doi.org/10.3390/su13179963
2. Neufeld, L., Stassen, F., Sheppard, R., Gilman, T.: The new plastics economy: rethinking the future of plastics. In World Economic Forum, vol. 7, January 2016

3. European Commission.: A European strategy for plastics in a circular economy (2018). Retrieved from https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:52018DC0028
4. Adams, K. T., Osmani, M., Thorpe, T., Thornback, J.: Circular economy in construction: current awareness, challenges and enablers. In Proceedings of the Institution of Civil Engineers-Waste and Resource Management, vol. 170, No. 1, pp. 15–24. Thomas Telford Ltd., 2017, February
5. Chen, Q., Feng, H., de Soto, B.G.: Revamping construction sup-ply chain processes with circular economy strategies: A systematic literature review. J. Clean. Prod., 130240 (2021)
6. Farooque, M., Zhang, A., Thürer, M., Qu, T., Huisingh, D.: Circular supply chain management: a definition and structured literature re-view. J. Clean. Prod. **228**, 882–900 (2019)
7. Stahel, W.R., Reday, G.: The potential for substituting manpower for energy, report to the Commission of the European Communities, Brussels (1976)
8. Stahel, W.R.: The product life factor. An Inquiry into the Nature of Sustainable Societies: The Role of the Private Sector (Series: 1982 Mitchell Prize Papers), NARC, pp. 74–96. (1982)
9. Ellen MacArthur Foundation (EMF) Towards the Circular Economy, vol. 1 (2013)
10. Stahel, W.R.: The circular economy. Nat. News **531**(7595), 435 (2016)
11. Zhou, L., Naim, M.M., Disney, S.M.: The impact of product returns and remanufacturing uncertainties on the dynamic performance of a multi-echelon closed-loop supply chain. Int. J. Prod. Econ. **183**, 487–502 (2017). https://doi.org/10.1016/j.ijpe.2016.07.021
12. Wei, S., Cheng, D., Sundin, E., Tang, O.: Motives and barriers of the remanufacturing industry in China. J. Clean Prod., Elsevier Ltd **94**, 340–351 (2015)
13. Seitz, M.A.: A critical assessment of motives for product recovery: the case of engine remanufacturing. J. Clean. Prod. **15**(11–12), 1147–1157 (2007)
14. Atasu, A., Guide, V.D.R., Jr., Van Wassenhove, L.N.: Product reuse economics in closed-loop supply chain research. Prod. Oper. Manag. **17**(5), 483–496 (2008)
15. Miemczyk, J., Howard, M., Johnsen, T.E.: Dynamic development and execution of closed-loop supply chains: a natural resource-based view. Supply Chain. Manag.: Int. J. (2016)
16. Holgado, M., Aminoff, A.: Closed-loop supply chains in circular economy business models. In: International Conference on Sustainable Design and Manufacturing, pp. 203–213. Springer, Singapore, June 2019
17. Batista, L., Gong, Y., Pereira, S., Jia, F., Bittar, A.: Circular supply chains in emerging economies–a comparative study of packaging recovery ecosystems in China and Brazil. Int. J. Prod. Res. **57**(23), 7248–7268 (2019)
18. Gosling, J., Naim, M., Towill, D.: Identifying and categorizing the sources of uncertainty in construction supply chains. J. Constr. Eng. Manag. **139**(1), 102–110 (2013)

# A Review of Failure Mode and Effects Analysis (FMEA) for Sustainable Manufacturing and Improvement in Electrostatic Chuck Manufacture and Operation

Steffan James(✉) and Hefin Rowlands

University of South Wales, South Wales Business School, Pontypridd CF37 1DL, Wales, UK
Steffan.James@southWales.ac.uk

**Abstract.** Failure modes and effect analysis (FMEA) is widely used in industry to quantify, mitigate, and eliminate risk for products and processes. It has the potential to be an important technique in supporting sustainable manufacturing by reducing the risks associated with transitioning to more sustainable processes. Whilst traditional FMEA does quantify risk by calculating a risk priority number (RPN), there are limitations to the usefulness of this due to the lack of objectiveness inherent in the method. In this paper improvements to the traditional FMEA approach are reviewed and their appropriateness in the specific case of the manufacture of electrostatic chucks (ESC) is considered.

**Keywords:** FMEA · Fuzzy FMEA · Electrostatic chuck

## 1 Introduction

Transitioning and changing existing manufacturing processes to more sustainable methods carries inherent risks. Badurdeen and Jawahir [1] argue that establishing a business case for sustainable manufacturing requires systems and procedures which facilitate sustainable manufacturing and create value for the organisation. Enyoghasi and Badurdeen [2] highlight opportunities for sustainable manufacturing through Industry 4.0 technologies. The potential for, and impact of, Failure Mode and Effect Analysis (FMEA) on enabling sustainable manufacturing is a developing area of research. Boral et al. [3] go as far as describing their novel approach to FMEA an essential requirement for sustainable manufacturing. Nguyen et al. [4] also proposed a novel method of FMEA with the intention of facilitating sustainable manufacturing. Malsch et al. [5] researched sustainable manufacturing of nanomaterials and the role of risk mitigation which is at the core of FMEA analysis.

This paper outlines part of the research undertaken during a collaborative project between 3 Universities in Wales (University of South Wales, Swansea University and Cardiff University) and SPTS Technologies, a division of KLA, based in Newport, South Wales. The SPTS Division of KLA provides advanced wafer processing solutions to the world's leading semiconductor and microelectronic device manufacturers


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 159–167, 2023.
https://doi.org/10.1007/978-981-19-9205-6_15

and designs, manufactures, sells and supports semiconductor manufacturing equipment. Their equipment provides advanced wafer processing technologies and solutions for the semiconductor and microelectronics industry.

The project aims to extend the understanding of electrostatic chuck (ESC) operation to improve wafer processing and to support the company's sustainable manufacturing goals. The project is divided into three parts, (1) The development of a computer model of the ESC to replicate its operation and simulate possible failure conditions, (2) Research into the use of FMEA as a technique to record, analyse and manage failure modes and (3) To explore the potential of industrial Internet of Things (IIoT) devices linked with the equipment for real time data analytics. This paper covers the work carried out in part 2 above, which is to review the wide range of FMEA hybrid approaches developed and to consider their applicability for failure identification within both the ESC and its manufacturing process.

The paper is structured as follows: Sect. 2 provides a description of an ESC, Sect. 3.1 provides a brief introduction to FMEA and explores the drawbacks of the standard FMEA approach. In Sect. 3.2 a critical review of FMEA literature is carried out with a focus on research articles describing enhancements to the traditional approach. Section 4 is the conclusion and future work.

## 2 Electrostatic Chuck

The Electrostatic Chuck (ESC) is a key component in semi-conductor manufacturing and is used in the etch and deposition process. It is subject to a number of complex interactions during use, often in extreme conditions such as low or high temperatures, vacuum environments, gas plasma, high voltage, and RF power. By applying a bipolar voltage to its internal electrodes, a directional electric field is created, and positive and negative charges drift within the material to match the polarity of the ESC's internal electrode. This attracting force between the ESC and the material allows it to be used to clamp or pick up silicon wafers as substrate materials [6].

Its manufacture is typically a fixed assembly of a bonded aluminum or titanium body with sealed internal cavities, RTV (room-temperature-vulcanizing) silicone, conductive epoxies, sputters metal layer and alumina ceramic. The final assembly is tested for its surface flatness, parallelism, roughness and internal bonds all of which are critical to quality.

Due to the complex nature of ESCs, and with limited access to internal components and layers, once assembled, failure modes and causes of failures are difficult to identify. A better understanding of the failures can lead to improved and more efficient production methods and provide opportunities for improved working practices and employee wellbeing. ESCs contain some components that cannot be reclaimed or recycled – principally the RTV silicone and ceramic (Alumina). Improved sustainability can be achieved through more reliable ESCs thus reducing failures and scrap rates. Greater reliability in the product can lead to more efficient semiconductor processing helping to relieve impact on the global semiconductor market where shortages are on the increase.

The next section explores the use of FMEA as a technique to identify, understand and manage the risk of failures.

# 3 FMEA Background and Critical Evaluation

## 3.1 Failure Mode and Effect Analysis: Background

FMEA is a systematic procedure for analysing the risks of a system to potential failure modes, their causes and effects on system performance. FMEA has been used as a technique in manufacturing since the late 1960s and was popularised in the automotive industry in the 1970s. Its origins go back further to the end of the 1940s where it was used by the US military to assess aircraft safety [7]. Today, whilst its use is commonplace in manufacturing industries, it has not endured the popularity of other quality methods promoted by lean and six sigma approaches. However, risk management is becoming increasingly important with an increased focus on sustainable manufacturing within an Industry 4.0 environment.

FMEA is based on conducting an analysis based on know-how and engineering decisions to generate occurrence, severity, and detection values. An RPN (Risk Priority Number) is calculated by multiplying OxSxD, where:

- Occurrence (O) is the probability of occurrence of the defect,
- Severity (S) is the significance of the defect/undesirable state,
- Detection (D) is the possibility of detection of the defect.
- Each parameter is typically assigned a numerical value from 1 to 10 [8] or can be assigned a linguistic value (see Table 1).

**Table 1.** Typical numerical and linguistic values assigned to O, S and D parameters

| Occurrence (O) | | Severity (S) | | Detection (D) | |
|---|---|---|---|---|---|
| 1 | Negligible | 1 | Meaningless | 1 | Very high |
| 2–3 | Occasional | 2–3 | Low | 2–3 | High |
| 4–6 | Moderate | 4–6 | Moderate | 4–6 | Moderate |
| 7–8 | High | 7–8 | High | 7–8 | Low |
| 9–10 | Very high | 9–10 | Very high | 9–10 | Accidental |

The risk level (indicated by the value of RPN) can have a value up to a maximum of 1000. In practice, the upper limits of this index which can be defined as the level of acceptability of risk, is arbitrary assigned. It is often assumed that an RPN less than 120 means an acceptable level of risk [10, 11].

FMEAs can be used at different stages of a project to achieve different outcomes.

- Design FMEA - used for the purpose of identification and prevention of failure modes of products, which are related to their design, in order to validate the established design parameters for a specific functional performance level, at system, subsystem or component level,

- Process FMEA - This type of FMEA focuses on potential failure modes of the process that are caused by manufacturing or assembly process deficiencies,
- Concept FMEA - The concept FMEA is used to analyse concept in the early stages before hardware is defined (most often at system and subsystem level).

Whilst the application of a traditional FMEA is well established with many templates and software tools available to support the process, it does have its limitations and relies heavily on the existing knowledge and data and it is not easy for engineers to express their evaluation of the risk factors in numerical terms [9]. Linguistic categories can be used to overcome this where three or five level can be used (See Table 1 for a 5-level example). Another limitation is that the RPN calculation overlooks relative importance amongst risk factors where O, S and D values are assumed to be of the same significance [8, 10, 11]. Also, in this case, different combinations of O, S and D values can provide the same RPN value, but in reality their risk priorities may differ [8]. Although this suggest that O, S and D values should be weighted relative to each other, assigning weights is not straightforward. [12] in their comprehensive literature review of FMEA also include interdependencies amongst failure modes and the limitation of only considering 3 risk factors (O,S,D) as further shortcomings which are not taken account in the traditional RPN calculation.

To overcome these limitations many researchers have explored alternative methods for implementing and evaluating FMEA RPN values to provide a more reliable risk ranking. The next section explores and evaluates alternatives to the standard FMEA approach.

### 3.2 Critical Review of FMEA

A classification of evaluation methods to improves or enhance the standard FMEA approach is provided in [12]. The most popular category is AI, accounting for 40% of the papers reviewed. This category is dominated by a Fuzzy systems approach. Integrated approaches account for 11.25% of papers which also include a number of integrated Fuzzy methods. The Multi Criteria Decision Methods (MCDM) account for 22.5% of papers and include Analytical Hierarchy Process (AHP), Analytic Network Process (ANP), The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Grey, decision making trial and evaluation laboratory (DEMATEL) and Multicriteria Optimization and Compromise Solution (VIKOR - from Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje). Also included in the MCDM category are Fuzzy variant of the above (For a detailed review of MCDM methods and their applications see [13]).

In adding to the review by [12], papers post 2012 in Table 2 also show a dominance of Fuzzy and MCDM approaches. For Fuzzy approaches see [10] and [14], for combinations of Fuzzy and other approaches (integrated approaches) see [8, 11, 15–18] and for MCDM techniques see [7, 11].

Other techniques have been explored including combining FMEA with other Quality tools such as QFD for supporting the decision-making process [19, 20], and the Taguchi method to explore combinations of decision criteria to minimise risk values [21].

Table 2 lists some of the FMEA hybrid analysis techniques developed in recent years with an indication of their application area.

In Table 2, focusing specifically on Fuzzy approaches, [10] and [14] use a Fuzzy rule based method to rank the PRN numbers and compare the Fuzzy results with the classical calculations. Differences in rankings of failure modes were observed between classical and Fuzzy FMEA and the authors claim improvements in using the Fuzzy approach due to overcoming drawback of equal weighting of the O, S and D values in the traditional approach although there was no objective measure of this improvement. In both classical and Fuzzy approaches the failure modes were determined using expert opinion. In [8], instead of using a fuzzy rule based approach, use a Fuzzy MCDM approach based on Fuzzy TOPSIS and Fuzzy AHP, where experts use linguistic variables to determine O,S, D values. This approach also overcomes drawback of assigning equal importance to O,S and D values.

A Fuzzy TOPSIS AHP approach was also adopted in [16], with the addition of 2 alternative evaluation criteria to the traditional S and D criteria and instead use two criteria related to maintenance management along with the traditional O. Sensitivity analysis was performed to test the influence of criteria weights.

Expert evaluation was also used by [15] to calculate the RPN values by applying a novel integration model based on an interval type–2 Fuzzy (IT2F) inference approach. This approach was designed specifically for group decision making where the main advantage of this approach in that it enables evaluations from different area of expertise to be assessed and combined. The authors claim the approach to be an improvement on a traditional FMEA in that it overcomes the limitation of different O,S,D values giving the same RPN score thus missing a potential of a high value in one of the measures influencing the RPN value.

Whilst Fuzzy approaches remain the most popular approach to enhance FMEA analysis, its drawback is that it is characterized by only membership functions and initial information may be lost in the process [22]. In order to address this shortcoming, the authors have developed the Interval-valued Intuition fuzzy sets (IVIF) approach to deal with uncertainty and incompleteness of information along with COPRAS and ANP (an extension of AHP) to address the MCDM aspects. This approach was applied to a case study in a hospital department setting. In this case, O, S and D values were further sub divided into 2 or 3 sub factors. IVIF was used to construct pair-wise comparison matrices between risk factors and sub-risk factors. The method was evaluated by comparing the results with both a traditional FMEA and a GRA-based FMEA. Distinct differences were reported between the traditional FMEA and the new model. The new model is able to distinguish and assign different priority levels to Failure modes that score the same RPN using the traditional method. Uncertainty is handled by IVIF-ANP and ranking handled by IVIF-COPRAS. However the approach still relies on expert knowledge and experience to develop the weighting of risk factors.

IVIF were also used by [11], where an integrated IVIF and Multi Criteria Broader Approximation area Comparison (MABAC - a new form of Multi Criteria Decision Analysis (MCDA)) method was developed. This approach has merits in that it recognises that information about risk factor weights is often only partially known or understood.

**Table 2.** FMEA Hybrid methods and their application areas

| FMEA Hybrid Technique(s) | Application area | Reference |
|---|---|---|
| Fuzzy | Sterilization unit in a large hospital | [10] |
| Fuzzy | Supercritical water gasification system | [14] |
| Fuzzy, TOPSIS, AHP | Hypothetical case of a Manufacturing facility in the automotive industry | [8] |
| Fuzzy, TOPSIS, AHP | Development of a new street cleaning vehicle with a telediagnosis system | [16] |
| Fuzzy IT2 (interval type 2) integrated model | Furniture manufacturing company | [15] |
| Complex Proportional Assessment (COPRAS), Analytic Network Process (ANP), Interval-valued intuitionistic Fuzzy Sets (IVIFS) | Hospital service setting | [22] |
| IVIF, MABAC - Results compare with Fuzzy-VIKOR and Intuitionistic fuzzy TOPSIS (IF-TOPSIS) | Radiation therapy process at cancer treatment centres | [11] |
| Fuzzy, AHP, MULTIMOORA | Occupational accidents at a steel factory | [17] |
| Fuzzy, Possibility theory | EOT crane for material handling | [18] |
| Fuzzy QFD | Shoe Manufacturing | [23] |
| Process Activity Mapping (PAM) | Low volume, high integrity manufacturing | [24] |
| AHP, Composition of Probabilistic Preferences (CPP) | Oil and gas sector services | [7] |
| VIKOR | Customer-oriented: 1. Ticket issuing service at a travel agent; 2. Movie theatre service | [25] |
| Action Research based approach | New Product Development (NPD) in the hydro-sanitary industry: manufacture of flush toilets – flush control board | [26] |
| FTA | Additive manufacturing system for metal printing | [27] |
| QFD | Steel manufacturing: Blast furnace operation | [19] |
| QFD-System Dynamics (SD) -Causal Loop Diagram (CLD) | Steel manufacturing: Roller transmission system | [20] |
| Process-Aware (PA) using Delphi, AHP, BPM life cycle | White goods manufacturing: end of assembly line | [28] |
| Expectation Interval, Taguchi, MOORA and Geometric Mean (GM) | Fuel oil system of a marine diesel engine | [21] |

A Fuzzy based approach to determine weights of O, S and D parameters using an extended Fuzzy AHP and Fuzzy Multiple multi-objective optimization by ratio analysis (MULTIMOORA) for MCDM evaluations was adopted by [17]. In this case the criteria of Cost, time and profit are used to calculate the weights of each failure mode.

All the above methods have combined or integrated Fuzzy approaches with other methods, mainly MCDM, using information drawn from experts. Whilst this can be a positive aspect where there is a lot of inherent knowledge in existence, the disadvantage is when the existing knowledge on a product or process is unknown or poorly understood.

## 4 Conclusion and Future Work

The adoption of FMEA as a risk mitigation tool in industry is now widespread and it is an expectation of many regulated industries that the procedures are followed. Whilst some consideration of risk is better than no consideration of risk, the limitations of traditional process and design FMEAs are repeatedly shown in the literature. The regulatory requirement to have an FMEA document often results in a box-ticking exercise of little value. The reliance on opinions and subjective scoring results in unquantifiable risks which cannot be compared across processes. FMEAs, particularly concept FMEAs, can support the development of sustainable manufacturing processes by evaluating risk before implementation, however traditional FMEAs have many shortcomings due to the subjectiveness of the process.

Alternative FMEA methodologies are becoming more frequently applied in industry, as seen in this literature review. Novel hybrid FMEA methodologies are numerous and the literature shows that, in practice, they are more effective in quantifying risks than the standard FMEA approach. This will provide industry with more confidence in taking on risk when developing new products or processes.

In general techniques utilizing a Fuzzy approach are the most widely used methods as it provides a mechanism to translate crips values for O,S, D measures into linguistic valuables for the Fuzzy approach to analyse. In the short term, a standard FMEA has its merits and provides a good starting point for developing more in-depth knowledge of a complex product such as ESC [29]. However more work is needed to evaluate the effectiveness of applying Fuzzy FMEA or other hybrid approaches to a complex product such as an ESC where access to internal structures is limited making it difficult to assess causes of failures.

There is a lot of existing knowledge and understanding of ESC operation in the literature and within the company which makes many of the approaches reviewed in this paper suitable where expert knowledge is needed for the FMEA development. The IVIF approaches developed by [22] and [11] are potentially suitable for this application where uncertainty and incomplete information can be accommodated. Also the approach by [15] has merits in that it is applicable for group work where knowledge from experts from different areas of expertise can be combined. This can be of advantage to the company where data from customers using their products can be gathered and integrated into the model.

The outcome of this literature review will be utilized in an ongoing research project to improve the manufacturing process and design of an electrostatic chuck, with the intention of improving the overall sustainability of the operations.

**Acknowledgements.** The ASTUTE 2020 (Advanced Sustainable Manufacturing Technologies) operation is part funded through the European Regional Development Fund (ERDF), the participating Higher Educational Institutions in Wales and KLA, SPTS Division, Newport, South Wales.

## References

1. Badurdeen, F., Jawahir, I.S.: Strategies for value creation through sustainable manufacturing. Procedia Manuf. **8**, 20–27 (2017)
2. Enyoghasi, C., Badurdeen, F.: Industry 4.0 for sustainable manufacturing: Opportunities at the product, process, and system levels. Resour., Conserv. Recycl. **166**, 105362 (2021)
3. Boral, S., Howard, I., Chaturvedi, S., Mckee, K., Naikan, V.: A novel hybrid multi-criteria group decision making approach for failure mode and effect analysis: An essential requirement for sustainable manufacturing. Sustain. Prod. Consum. **21**, 14–32 (2020)
4. Nguyen, T.-L., Shu, M.-H., Hsu, B.-M.: Extended FMEA for sustainable manufacturing: an empirical study in the non-woven fabrics industry. Sustainability **8**(9), 939 (2016)
5. Malsch, I., Subramanian, V., Semenzin, E., Hristozov, D.: Supporting decision-making for sustainable nanotechnology. Environ. Syst. Decis. **35**(1), 54–75 (2015)
6. Wang, L.-E., Liu, H.-C., Mei-Yun Quan, M.-Y.: Evaluating the risk of failure modes with a hybrid MCDM model under interval-valued intuitionistic fuzzy environments. Comput. Ind. Eng. **102**, 175–185 (2016)
7. de Souza, F.H., Gaviao, L.O., Sant'anna, A.P., Lima, G.B.A.: Prioritising risks with composition of probabilistic preferences and weighting of FMEA for fast decision making in complex scenarios. Int. J. Manag. Proj. Bus. **15**(4), 572–594 (2021)
8. Kutlu, A.C., Ekmekçioğlu, M.: Fuzzy failure modes and effects analysis by using fuzzy TOPSIS-based fuzzy AHP. Expert. Syst. Appl. **39**, 61–67 (2012)
9. Cabanes, B., Hubac, S., Lemasson, P., Benoit, W.: Improving reliability engineering in product development based on design theory: the case of FMEA in the semiconductor industry. Res. Eng. Des. **32**(3), 309–329 (2021)
10. Dagsuyu, C., Gocmen, E., Narli, M., Kokangul, A.: Classical and fuzzy FMEA risk analysis in a sterilization unit. Comput. Ind. Eng. **101**, 286–294 (2016)
11. Liu, H.-C., You, J.-X., Duan, C.-Y.: An integrated approach for failure mode and effect analysis under interval-valued intuitionistic fuzzy environment. Int. J. Prod. Econ. **207**, 163–172 (2019)
12. Liu, H.-C., Liu, L., Liu, N.: Risk evaluation approaches in failure mode and effects analysis: a literature review. Expert. Syst. Appl. **40**, 828–838 (2013)
13. Mardani, A., Jusoh, A., Nor, K.M., Khalifah, Z., Zakwan, N., Valipour, A.: Multiple criteria decision-making techniques and their applications—a review of the literature from 2000 to 2014. Econ. Res.-Ekon. Istraz. **28**(1), 516–571 (2015)
14. Adar, E., Ince, M., Karatop, B., Bilgili, M.S.: The risk analysis by failure mode and effect analysis (FMEA) and fuzzy-FMEA of supercritical water gasification system used in the sewage sludge treatment. J. Environ. Chem. Eng. **5**, 1261–1268 (2017)
15. Golcuk, I.: Interval type-2 fuzzy interence-based failure mode and effect analysis model in a group decision-making setting, Kybernetes, Vol. ahead of print (2021)
16. Carpitella, S., Certa, A., Izquierdo, J., La Fata, C.M.: A combined multi-criteria approach to support FMECA analyses: a real-world case. Reliab. Eng. Syst. Saf. **169**, 394–402 (2018)
17. Fattahi, R., Khalilzadeh, M.: Risk evaluation using a novel hybrid method based on FMEA, extended MULTIMOORA, and AHP methods under fuzzy environment. Saf. Sci. **102**, 290–300 (2018)

18. Mandal, S., Maiti, J.: Risk analysis using FMEA: Fuzzy similarity value and possibility theory based approach. Expert. Syst. Appl. **41**, 3527–3537 (2014)
19. Shaker, F., Shahin, A., Jahanyan, S.: Developing a two-phase QFD for improiving FMEA: an integrative approach. Int. J. Qual. Reliab. Manag. **36**(8), 1454–1474 (2019)
20. Shaker, F., Shahin, A., Jahanyan, S.: Investigating the causal relationships among failure modes, effects and causes; a system dynamics approach. International Journal of Quality and Reliability Management, Vol. ahead of print (2021)
21. Emovon, I., Mgbemena, C.O.: Enhancing the FMEA technique using a combination of Expectation interval, TAGUCHI, MOORA and Geometric Mean methods. J. Eng. Res. **7**, 238–260 (2019)
22. Wang, X.K., Cheng, J., Wang, K.S., Yang, Y.Y., Sun, Y.C., Cao, M.L., Han, C.K., Ji, L.H.: Modeling of electrostatic chuck and simulation of electrostatic force. In: Applied Mechanics and Materials, vol. 511–512 (Sensors, Mechatronics and Automation), pp. 588–594 (2014)
23. Reda, H., Dvivedi, A.: Decision-making on the selection of lean tools using fuzzy QFD and FMEA approach in the manufacturing industry. Expert. Syst. Appl. **192**, 116416 (2022)
24. Marriott, B., Arturo Garza-Reyes, J., Soriano-Meier, H., Antony, J.: An integrated methodology to prioritise improvement initiatives in low volume-high integrity product manufacturing organisations. J. Manuf. Technol. Manag. **24**, 197–217 (2013)
25. Hettiarachchi, R.L., Koomsap, P. & Ardeneam, P. 2021. VIKOR power law-based customer-oriented FMEA with complete unique risk priority numbers. International Journal of Quality & Reliability Management, Vol. ahead of print.
26. Moreira, A.C., Ferreira, L.M.D.F., Silva, P.: A case study on FMEA-based improvement for managing new product development risk. Int. J. Qual. Reliab. Manag. **38**, 1130–1148 (2021)
27. Peeters, J.F.W., Basten, R.J.I., Tinga, T.: Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner. Reliab. Eng. & Syst. Saf. **172**, 36–44 (2018)
28. Filho, J.C.B., Piechnicki, F., de Freitas Rocha Loures, E., Santos, E.A.P.: Process-aware FMEA framework for failure analysis in maintenance. J. Manuf. Technol. Manag. **28**(6), 822–848 (2017)
29. Sana, M., Saleem, U., Farooq, M., Qamar, A., Bhutta, M., Zafar, S.: Identification of failure modes on electrostatic chuck through reliability centered maintenance: a case study. Proc Pak. Acad. Sci. A **55**(2), 21–32 (2018)

# Novel Design and Simulation Approach for a Piezoelectric Micropump with Diffusers

Shanuka Dodampegama[1](✉), Amith Mudugamuwa[1], Menaka Konara[1], Gehan Melroy[1], Uditha Roshan[2], Ranjith Amarasinghe[1,2], Peihong Wang[3], and Van Dau[4]

[1] Accelerating Higher Education Expansion and Development (AHEAD) Project – Centre for Advanced Mechatronic Systems, University of Moratuwa, Katubedda 10400, Sri Lanka
shanukakamesh@gmail.com
[2] Department of Mechanical Engineering, University of Moratuwa, Katubedda 10400, Sri Lanka
[3] School of Physics and Materials Science, Anhui University, Hefei 230601, China
[4] School of Engineering and Built Environment, Griffith University, Gold Coast, Australia

**Abstract.** This paper presents a computer-based design approach of a piezoelectric valveless micropump which consists of a piezoelectric element, a diaphragm, a pump chamber, two diffusers, an inlet, and an outlet. The diaphragm and the piezoelectric element act as the actuator of the micropump. In the study, geometric parameters of the actuator, diffusers and external parameters are numerically analyzed in a Multiphysics environment using structural analysis and fluid structure interaction (FSI) simulations. At first, the ratios between the diameters and the thicknesses are evaluated considering the maximum volumetric change of the diaphragm for a specific frequency and voltage. Then, the trends of the flow rate against the geometric parameters of the diffusers of the micropump are investigated to select suitable geometric parameters based on the flow rate. Furthermore, the effect of external parameters on the flow rate is studied. A direct relationship is observed between the displacement of the diaphragm and the applied voltage. The flow rate of the micropump increases exponentially when the width of the short side and the length of the diffuser decreases. Additionally, curve fitting is used to identify the relationship of flow rate with the applied voltage and the operating frequency which showed a quadratic and linear relationship respectively.

**Keywords:** Micropump · FSI simulations · Parameter optimization · Piezoelectric actuation · Lab on a Chip · Diffuser · Valveless

## 1 Introduction

Microfluidics is an emerging technology that deals with manipulating and processing micro-scale fluid volumes. Rapid advancements in Micro Electromechanical Systems (MEMS) have contributed to the evolution of microfluidic systems in the last decade and the use of bio-compatible materials has provided novel directions in developing


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 168–180, 2023.
https://doi.org/10.1007/978-981-19-9205-6_16

MEMS-based microfluidic devices, suitable for biomedical applications [1]. MEMS-based microfluidic devices such as Lab-on-a-Chip (LOC) devices for Point-of-Care (POC) diagnostics, Micro Total Analysis Systems (μTAS), targeted drug delivery systems, and implantable devices are reported [2]. Fluid transportation is widely used in these types of microfluidic systems. A micropump is a special type of microfluidic device that is used to transport microliter scale fluid volumes in microchannels. Regardless of being continuous flow-based microfluidic systems [3] or droplet-based microfluidic systems [4], the characteristics of the fluid flow inside microchannels affect the overall functionality of the device's effectiveness and efficiency.

Micropumps are mainly categorized as active and passive pumps. Active micropumps are further categorized as mechanical and non-mechanical micropumps [5, 6]. Micropumps can also be categorized as micropumps with valves and without valves (or valveless). According to the literature mechanical micropumps use various types of physical phenomena such as piezoelectric, electrostatic, thermo-pneumatic, shape memory alloys, bimetallic, ion conductive polymer film, electromagnetic, and phase change [7]. Among these types, piezoelectric micropumps have higher flow rates due to their high response rates [8]. In addition to the actuator, micropumps require check valves or diffusers to maintain a net directional flow rate [9]. Micropumps with check valves can generate a higher flow rate, but their durability is low due to the wear and tear of the moving parts in the check valve. Conversely, micropumps with diffusers (valveless micropumps) do not have any moving parts, but their flow rates are low [10].

Sustainable design techniques and computer-based analysis methods have enabled the investigation of miniature systems and understand complicated functionalities prior to device fabrication, which significantly reduce the cost at the design stage. Conservation of resource, lower time-consumption, minimum waste production, and minimum energy consumption are few advantages of computer based sustainable design techniques. The literature presents the use of various computer-based simulation and analysis techniques to investigate the parameters related to different actuation mechanisms of MEMS-based microfluidic devices on the functionality and performance of the devices [11]. FSI, flow analysis, and stress analysis are conducted to evaluate the performance of the micropumps [12]. The behavior of the diaphragm and diffusers of the valveless piezoelectric micropumps are used to investigate the performance of the overall micropump. Fan et al. numerically analyzed the effect of the applied frequency on the deflection of the diaphragm at a range from 50 Hz to 50 kHz [8]. Cui et al. conducted simulations using the Ansys software to find an optimal thickness for the piezoelectric element. According to their results, it is affected by material and the thickness of the pump membrane [13]. In the study, a mathematical model is developed, valveless piezoelectric micropump is numerically analyzed, and parameters related to the piezoelectric element are investigated [14]. Dereshgi et al. numerically analyzed the operation of a valveless piezoelectric micropump with single and dual diaphragm arrangements at a low-frequency range [15]. Therefore, the literature provides the background to analyze the parameters related to the piezoelectric element, the diaphragm, and the micropump design using computational engineering techniques. Iterative design optimization capability of these techniques improves the efficiency and productivity of the overall manufacturing process by eliminating the drawbacks of the commonly used 'trial and error' approach. Comparatively, shorter lead times have encouraged the use of computational engineering modelling, simulation, and implementation of sustainable manufacturing technologies for research and industrial product development.

In designing a valveless micropump, it is important to identify the key parameters that affect the performance of the pumping device. The effect of the geometric parameters and the external parameters on the flow rate of the micropump is analyzed by computational methods, to understand the performance of the micropump. Additionally, optimization of these parameters is essential in designing a micropump to deliver the required flow rate to the microfluidic system. In this paper, we present an analysis of a valveless micropump with a piezoelectrically actuated diaphragm using COMSOL Multiphysics software. Numerical simulations are conducted to find the relationship between the ratio between the thickness and diameter of the piezoelectric element and the diaphragm, and the deflection of the diaphragm for different voltages and frequencies. Then, the relationship between the flow rate of the micropump and the parameters of the diffusers is studied numerically. The observations and the results provide a novel approach for developing micro-scale pumping using piezoelectric materials and provide optimum parametric values required for prototyping the devices.

## 2 Proposed Micropump

The micropump consists of a pump chamber, diaphragm, piezoelectric element, inlet, and outlet as shown in Fig. 1. Two diffusers are used in the inlet and outlet; therefore, the pump is categorized as a valveless micropump. The diaphragm is placed in between the piezoelectric element and the pump chamber to avoid cross-contamination between the working fluid which is favorable in developing biocompatible microfluidic devices.

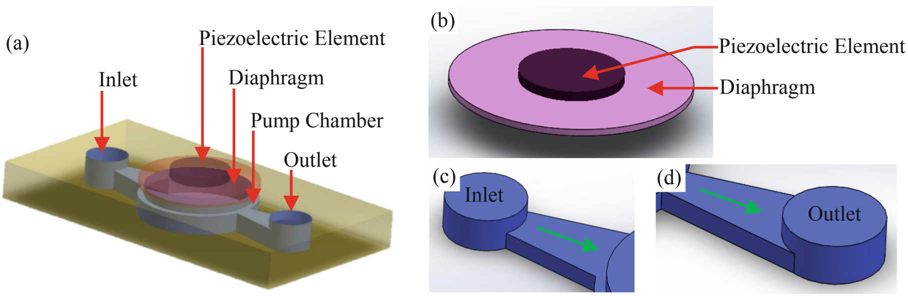
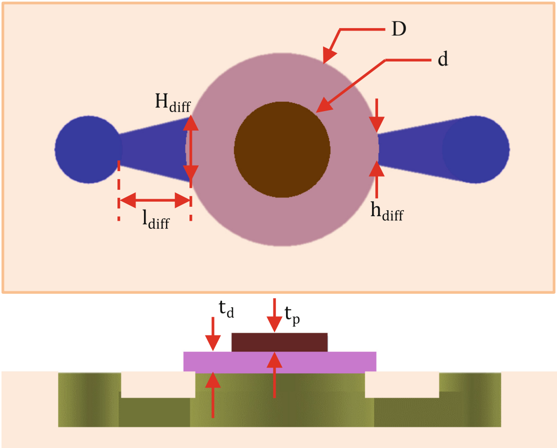



**Fig. 1.** (a) Proposed system layout and subcomponents; (b) Piezoelectric element and diaphragm; (c) Inlet diffuser; (d) Outlet diffuser. Green arrows represent the flow direction (Color figure online).

Based on the literature, the diameter and the thickness of the diaphragm and piezoelectric element, length, and widths of the two sides of the diffuser are identified as the dominating geometric parameters in designing the micropump [10]. Operating frequency and applied voltage are the external variables considered in controlling the micropump [16].

## 3 Methodology

At first, the parameters related to the diaphragm are analyzed. The design parameters are shown in Fig. 2. Then, the results are used to analyze the parameters related to the diffusers.




$$\alpha = \frac{d}{D} \qquad \beta = \frac{t_d}{t_p} \qquad r_1 = \frac{h_{diff}}{H_{diff}} \qquad r_2 = \frac{l_{diff}}{H_{diff}}$$

**Fig. 2.** Design parameters and four ratios

To simplify the analysis, four ratios α, β, $r_1$ and $r_2$ which are shown in Fig. 2 are defined by using the following parameters.

d – Diameter of the piezoelectric element
D – Diameter of the diaphragm
$t_d$ – Thickness of the diaphragm
$t_p$ – Thickness of the piezoelectric element
$h_{diff}$ – Width of the small side of the diffuser
$H_{diff}$ – Width of the large side of the diffuser
$l_{diff}$ – Length of the diffuser

Since d and $h_{diff}$ are designed to be less than D and $H_{diff}$, α and $r_1$ are less than 1. β is varied from 0.2 to 5 and $r_2$ is varied from 0.25 to 5. The height of the microchannel ($t_{cha}$) is taken as 1 mm. The highest operating frequency and applied voltage are selected as 32 Hz and 400 V respectively for the analysis. Multiphysics simulations are carried out to obtain the data points of flow rates for different parameters. Then, a curve fitting technique is used to observe the trend between the flow rates and the parameters. Among the different piezoelectric materials used in previous piezoelectricity-based studies [17], Lead Zirconate Titanate (PZT) is the most commonly used piezoelectric element, due to its ability to achieve high deflections [14]. Therefore, PZT is selected as the material for the piezoelectric element in the presented study, and brass is selected as the diaphragm material to maintain the biocompatibility of the device. Table 1 shows the steps taken during the analysis of the micropump.

**Table 1.** Micropump analysis steps

| Observed parameter | Varied parameter | Fixed parameters | Desired outcome | Method/Technique |
|---|---|---|---|---|
| Maximum volumetric change | α | β, $r_1$, $r_2$, frequency, voltage | Diaphragm displacement at different points for different α | Parametric sweep |
| | | | Total volumetric change of diaphragm for different α | Surface integration |
| | | | Maximum volumetric change | Calculating the maximum value |
| | | | Obtaining the trend | Curve fitting |
| | β | α, $r_1$, $r_2$, frequency, voltage | Diaphragm displacement at different points for different β | Parametric sweep |
| | | | Total volumetric change of diaphragm for different β | Surface integration |
| | | | Maximum volumetric change | Calculating the maximum value |
| | | | Obtaining the trend | Curve fitting |
| Diaphragm deflection | Frequency, voltage | α, β, $r_1$, $r_2$ | Eigen frequencies of the diaphragm | Mode shape analysis |
| Diaphragm displacement | | | Diaphragms displacement vs frequency and voltage | Structural analysis |
| Diaphragm and piezoelectric element stress | Voltage | α, β, $r_1$, $r_2$, frequency | Maximum stress of diaphragm and piezoelectric element vs voltage | Structural analysis |
| Flow rate | Diffuser width | α, β, $r_2$, frequency, voltage | Flow rate vs $r_1$ | FSI simulation |
| | | | Obtaining the trend | Curve fitting |

(*continued*)

**Table 1.** (*continued*)

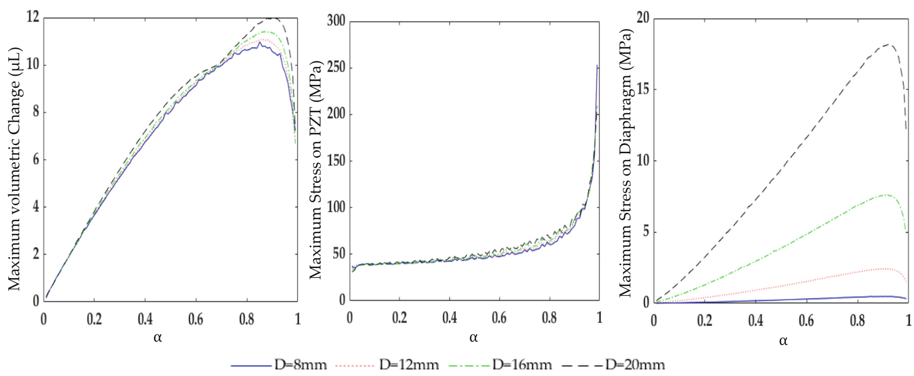
| Observed parameter | Varied parameter | Fixed parameters | Desired outcome | Method/Technique |
|---|---|---|---|---|
| | Diffuser length | α, β, $r_1$, frequency, voltage | Flow rate vs $r_2$ | FSI simulation |
| | | | Obtaining the trend | Curve fitting |
| | Frequency, voltage | α, β, $r_1$, $r_2$ | Flow rate vs voltage | FSI simulation |
| | | | Obtaining the trend | Curve fitting |
| | | | Flow rate vs frequency | FSI simulation |
| | | | Obtaining the trend | Curve fitting |

# 4 Results and Discussion

## 4.1 Variation of Maximum Volumetric Change

### 4.1.1 Maximum Volumetric Change with α

In this analysis, a voltage of 300 V is applied to the piezoelectric element with a frequency of 20 Hz. During this simulation β, $r_1$ and $r_2$ are kept constant at 0.5, 0.4, and 2. Variation of the maximum volumetric change with α obtained by the analysis for 4 different diameters of the diaphragm is shown in Fig. 3 (a). According to the results, the maximum volumetric change of the micropump increases with the diameter of the diaphragm for a specific α value. For a specific diameter of the diaphragms, the maximum volumetric change increases until α = 0.9 and then, decreases at a higher rate. Therefore, the maximum volumetric change is observed to be the highest at α = 0.9.



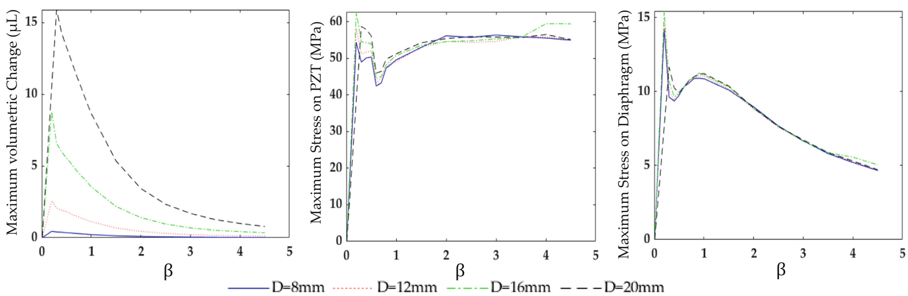

(a) (b) (c)

**Fig. 3.** (a) Maximum volumetric change; (b) Maximum stress on piezoelectric element; (c) Maximum stress on diaphragm vs $\alpha$, for 4 different diameters of the diaphragm

Variations of the stresses generated on the piezoelectric element and the diaphragm against α, for 4 different diameters are shown in Figs. 3 (b) and (c). According to the selected materials for the piezoelectric element and the diaphragm, the yield stress of PZT and brass are 114.8 MPa and 140 MPa. The results show that the stresses generated on the diaphragm, significantly reside below the yield stress. But according to the stresses generated on the piezoelectric element at the range of $\alpha > 0.95$, the element is at a risk of failing. Having a higher safety factor ensures the reliability of the functionality and the durability of the micropump. According to Fig. 3 (b), the safety factor of the piezoelectric element can be increased by lowering the α value. For the study, a higher safety factor of 2.2 is obtained by selecting α as 0.67 [18]. In addition, applications with high flow rate requirements, need the piezoelectric element to be actuated at higher frequencies. According to experiments conducted in a previous study by our research group, it was identified that the piezoelectric element have a higher possibility to fail in such instances [19]. Therefore, selecting a lower α value for the piezoelectric element is identified as appropriate to avoid failures during the operation of the micropump.

### 4.1.2 Maximum Volumetric Change with β

Similar to the previous analysis, a voltage of 300 V is applied to the piezoelectric element with an operating frequency of 20 Hz. Variation of the maximum volumetric change against β, for 4 different diameters of the diaphragm is shown in Fig. 4 (a). According to the results, it is observed that the volumetric change decreases when the value increases in the range of $\beta > 1$ and there is a peak in the range $\beta < 1$. The maximum volumetric change and the β value correspond to the increment of the peak increases when the diameter of the diaphragm is increased. Stress variation in both piezoelectric element and the diaphragm which are shown in Fig. 4 (b) and (c) do not pass the yield stresses of the materials. But there exists a local minimum near 0.5 in both of the stress graphs. Therefore, 0.5 is selected as the suitable value for β to proceed with the analysis. During this simulation α, $r_1$ and $r_2$ are kept constant at 0.67, 0.4, and 2.




(a) (b) (c)

**Fig. 4.** (a) Maximum volumetric change; (b) Maximum stress on piezoelectric element; (c) Maximum stress on diaphragm vs $\beta$ for 4 different diameters of the diaphragms.

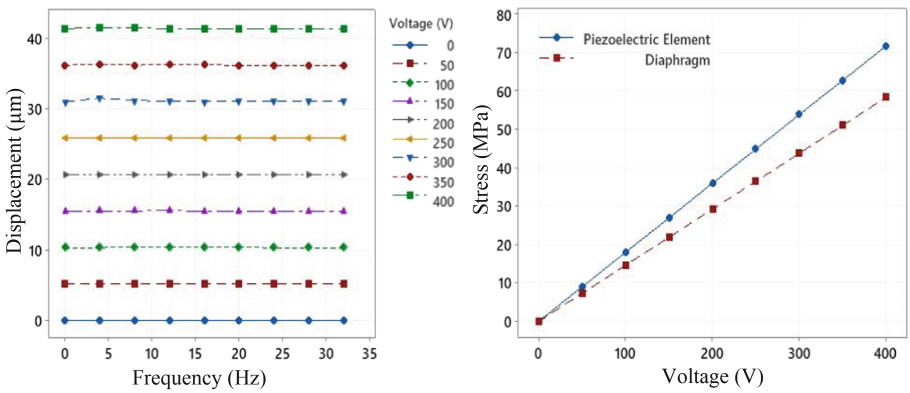
## 4.2 Deflection of the Diaphragm

The first and the second mode shapes of the diaphragm are shown in Fig. 5. According to the results, the center of the diaphragm has the maximum displacement when the operating frequency varies up to 7801.4 Hz. According to the design considerations, the highest operating frequency is below the first Eigen frequency. Therefore, the deflection of the diaphragm has the same deformation throughout the selected operating frequency range.

(a) (b)

**Fig. 5.** (a) First mode shape (7801.4 Hz); (b) Second mode shape (14972 Hz)

Results obtained by the displacement analysis are shown in Fig. 6 (a). In the graph, the maximum displacement of the center of the diaphragm is plotted against the applied voltage and operating frequency during one cycle of operation. According to the graph, the variation of displacement against the operating frequency does not show a significant change, but the displacement increases when the applied voltage is increased and achieves a maximum displacement of 42 μm for 400 V. Variation of maximum stress of the piezoelectric element and the diaphragm with the applied voltage during one operating cycle are shown in Fig. 6 (b). According to the graph, the stress generated on the piezoelectric element is higher than the stress generated on the diaphragm, and both have a linear variation with the applied voltage. Since the stresses are less than the yield stresses of the materials, the selected range of applied voltages and operating frequencies do not cause any failure in materials.




(a) (b)

**Fig. 6.** (a) Variation of displacement vs applied voltage and operating frequency; (b) Variation of the stress of piezoelectric element and diaphragm vs applied voltage.

## 4.3 Variation of Flow Rate with Diffuser Parameters and External Parameters

### 4.3.1 Flow Rate with Diffuser Width

The operating frequency and applied voltage are taken as 20 Hz and 300 V for the analysis. $r_2$ is kept constant at 2. Therefore, the diffuser length is 200 µm. Flow rates of the micropump for different $r_1$ values are plotted in blue color dots in Fig. 7 (a).

According to the simulations, it is identified that the flow rate reduces when increasing $r_1$. It conveys that, the performance of the micropump increases when the width of the short side of the diffuser keeps at low values compared to the other side. When $r_1$ is 0.1, the micropump has a flow rate of ~0.3 $\mu Ls^{-1}$. This value can be increased or decreased by changing the operating frequency and applied voltage. A curve is fitted to identify the relation between the flow rate and $r_1$ by using nonlinear regression. It is shown in the dashed line in Fig. 7 (a). The equation of the fitted curve is shown in Eq. (1).

$$y = 5.75985 \times e^{-4.81765x} \tag{1}$$

### 4.3.2 Flow Rate with Diffuser Length

$R_1$ is taken as 0.4 in this analysis. Since $H_{diff}$ is equal to 1 mm, $h_{diff}$ is 400 µm. The operating frequency and applied voltage are kept at 20 Hz and 300 V similar to the previous analysis. The flow rate for two complete cycles against different $r_2$ values is shown in Fig. 7 (b).

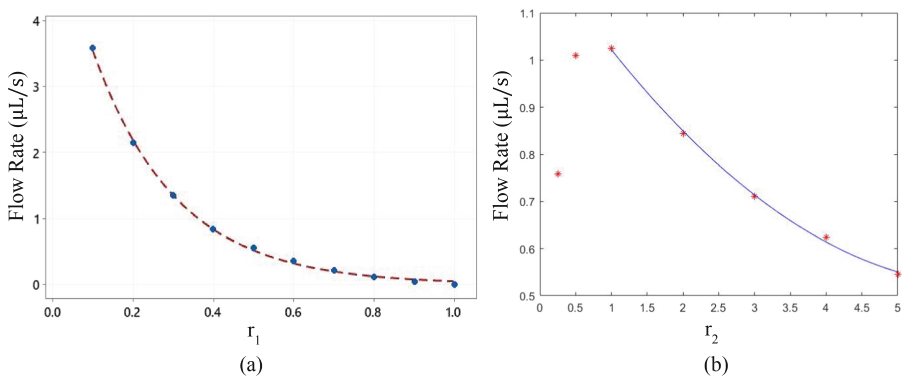



**Fig. 7.** (a) Variation of the flow rate of the pump vs $r_1$. The dashed line represents the fitted curve; (b) Red color dots represent the variation of the flow rate of the pump vs $r_2$; (b) Blue color line represents the fitted curve for $r_2 \geq 1$(Color figure online).

According to the results, it can be observed that the flow rate increases when $r_2$ decreases from 5 to 1. Afterward, the flow rate reaches a maximum and decreases when $r_2$ decreases from 1 to 0. The flow rate of the micropump for $r_2 \geq 1$ can be estimated by using nonlinear regression. The equation of the fitted curve is shown in Eq. (2) and the curve is shown in Fig. 7 (b).

$$y = 1.230 - 0.2264x + 0.01810x^2 \tag{2}$$

### 4.3.3 Flow Rate with Applied Voltage and Operating Frequency

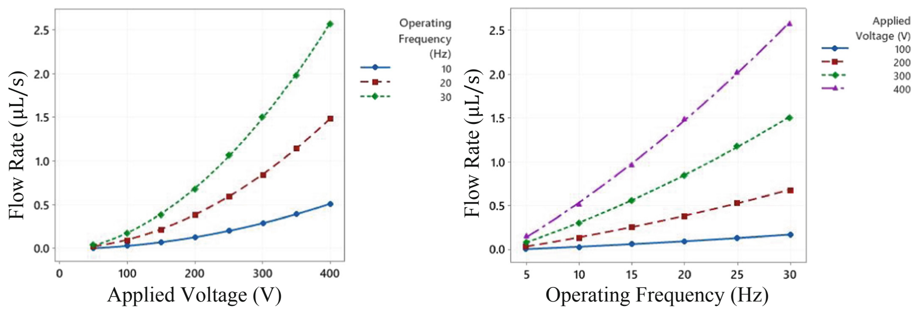
For this analysis, $r_1$ and $r_2$ are taken as 0.4 and 2. Since $H_{diff}$ is 1 mm, $h_{diff}$ and $l_{diff}$ are taken as 400 μm and 2 mm respectively. Figure 8 (a) shows the relationship between the flow rate of the micropump and the applied voltage for three different operating frequencies.

According to the results it can be examined that the flow rate and applied voltage have a quadratic relationship. Quadratic curves are fitted using polynomial regression analysis. Equations of the curves when the operating frequency is 10 Hz, 20 Hz, and 30 Hz are shown in Eqs. (3), (4), and (5) respectively. For the three curves, $R^2$ values are 100%.

$$y = -0.006614 + 0.00007578x + 0.000003066x^2 \tag{3}$$

$$y = -0.01012 + 0.0001978x + 0.000008852x^2 \tag{4}$$

$$y = -0.04301 + 0.0007396x + 0.00001454x^2 \tag{5}$$




(a) (b)

**Fig. 8.** (a) Variation of the flow rate of the micropump with the applied voltage for different operating frequencies; (b) Variation of the flow rate of the micropump with the operating frequency for different applied voltages.

Figure 8 (b) shows the relationship between the flow rate of the micropump and the operating frequency for four different applied voltages. According to the results it can be observed that the flow rate has a linear variation with the operating frequency. Straight lines are fitted using linear regression to verify the relationship. Equations of the lines when the applied voltage is 100 V, 200 V, 300 V, and 400 V are shown in Eqs. (6), (7), (8), and (9) respectively. $R^2$ values of four lines are 99.99%, 100%, 100%, and 100% respectively.

$$y = -0.01782 + 0.004466x \tag{6}$$

$$y = -0.05845 + 0.01684x \tag{7}$$

$$y = -0.1158 + 0.03565x \tag{8}$$

$$y = -0.2171 + 0.06561x \tag{9}$$

## 5 Conclusion

In this study, numerical analysis of a piezoelectric micropump with two diffusers is conducted while studying the relationships between maximum volumetric change with the diameter ratio $r_1$ and thickness ratio $r_2$ of the diaphragm and the piezoelectric element. Simulations have illustrated the highest volumetric change when $\alpha = 0.9$ and $\beta = 0.5$. Results also show that the amount of deflection of the diaphragm is directly proportional to the applied voltage, and it does not show any relation with the operating frequency. It has been observed that the flow rate of the micropump increases when the difference between the two widths of the diffuser increases. Initially, the flow rate increased with decreasing diffuser length but with a further reduction of diffuser length, the flow rate began to decrease. When the external parameters of the micropump are considered, flow rate against applied voltage has a quadratic relationship and flow rate against operating frequency has a linear relationship. In the proposed micropump, the highest operating frequency is 32 Hz, and the maximum applied voltage is set to be around 400 V. Multiphysics simulations and numerical analysis were conducted using COMSOL and MATLAB software platforms. According to the results obtained from the analysis, it is concluded that the use of diffusers in the micropump can generate a flow rate that is in the microliter range.

The micropump analysis reported in this paper can be used to design micropumps to provide desired flow rates. The study is specifically conducted for low-frequency range and low flow rate pumping applications. Furthermore, the performance of the diffusers can be improved by analyzing different geometries using curved surfaces and the micropump can be investigated for different working fluids to improve understanding of the functionality of the piezoelectric micropump proposed in the study.

**Acknowledgements.** The authors would like to express their gratitude to the Accelerating Higher Education Expansion and Development (AHEAD) - Development Oriented Research (DOR) grant of the Centre for Advanced Mechatronic Systems (CFAMS), University of Moratuwa, Sri Lanka for their financial contribution and the CFAMS for their valuable advice and guidance towards the success of the research.

## References

1. Hettiarachchi, S., et al.: Design and development of a microfluidic droplet generator with vision sensing for lab-on-a-chip devices. Sens. Actuators A: Phys. **332**, 113047 (December 2021). https://doi.org/10.1016/j.sna.2021.113047
2. Suriyage, M.P. et al.: Design and simulation of a novel MEMS based microfluidic circulating tumor cell (CTC) detection system for a lab on a chip device. IOP Conf. Ser.: Mater. Sci. Eng. **895**, 012016 (July 2020). https://doi.org/10.1088/1757-899X/895/1/012016

3. Liu, B., Dong, S., Tan, J., Li, D., Yang, J.: Design and flow simulation of a micro steam jet pump. Mod. Phys. Lett. B **36**(9), 2250018 (March 2022). https://doi.org/10.1142/S021798492250018X
4. 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, vol. 192, pp. 201–210. Springer Singapore, Singapore (2020). https://doi.org/10.1007/978-981-15-5852-8_19
5. Wang, Y.-N., Fu, L.-M.: Micropumps and biomedical applications – A review. Microelectron. Eng. **195**, 121–138 (August 2018). https://doi.org/10.1016/j.mee.2018.04.008
6. Hettiarachchi, S., Melroy, G., Mudugamuwa, A., Perera, N., Sampath, P., Amarasinghe, R.: 3D printed multi-channel peristaltic pump with active droplet generator for lab-on-a-chip devices. In: Scholz, S.G., Howlett, R.J., Setchi, R. (eds.) Sustainable Design and Manufacturing, vol. 262, pp. 235–244. Springer Singapore, Singapore (2022). https://doi.org/10.1007/978-981-16-6128-0_23.
7. Ashraf, M.W., Tayyaba, S., Afzulpurkar, N.: Micro electromechanical systems (MEMS) based microfluidic devices for biomedical applications. IJMS **12**(6), 3648–3704 (June 2011). https://doi.org/10.3390/ijms12063648
8. Fan, B., Song, G., Hussain F.: Simulation of a piezoelectrically actuated valveless micropump. Smart Mater. Struct. **14**(2), 400–405 (April 2005). https://doi.org/10.1088/0964-1726/14/2/014
9. Nisar, A., Afzulpurkar, N., Mahaisavariya, B., Tuantranont, A.: MEMS-based micropumps in drug delivery and biomedical applications. Sens. Actuators B: Chem. **130**(2), 917–942 (March 2008). https://doi.org/10.1016/j.snb.2007.10.064
10. Cui, Q., Liu, C., Zha, X.F.: Simulation and optimization of a piezoelectric micropump for medical applications. Int. J. Adv. Manuf. Technol. **36**(5–6), 516–524 (March 2008). https://doi.org/10.1007/s00170-006-0867-x
11. S. Hettiarachchi, A. Mudugamuwa, Amarasinghe, R.: Microfluidic channel network analysis of a lab-on-a-chip device using electrical circuit analogy. In: 2020 From Innovation to Impact (FITI), pp. 1–4. Colombo, Sri Lanka (December 2020). https://doi.org/10.1109/FITI52050.2020.9424888
12. Jeong, J., Kim, C.N.: A numerical simulation on diffuser-nozzle based piezoelectric micropumps with two different numerical models. Int. J. Numer. Meth. Fluids **53**(4), 561–571 (February 2007). https://doi.org/10.1002/fld.1294
13. Cui, Q., Liu, C., Zha, X.F.: Study on a piezoelectric micropump for the controlled drug delivery system. Microfluid Nanofluid **3**(4), 377–390 (June 2007). https://doi.org/10.1007/s10404-006-0137-0
14. Muralt, P.: Recent progress in materials issues for piezoelectric MEMS', J. Am. Ceram. Soc. **91**(5), 1385–1396 (May 2008). https://doi.org/10.1111/j.1551-2916.2008.02421.x
15. Asadi Dereshgi, H., Yildiz, M.Z.: Numerical study of novel MEMS-based valveless piezoelectric micropumps in the range of low voltages and frequencies. In: 2019 Scientific Meeting on Electrical-Electronics & Biomedical Engineering and Computer Science (EBBT), pp. 1–4. Istanbul, Turkey (April 2019). https://doi.org/10.1109/EBBT.2019.8741629
16. Nhu, C.N., Van, L.L., Ngoc, A.N., Dau, V.T., Bui, T.T., Duc, T.C.: A valveless micropump based on additive fabrication technology. IJNT **15**(11/12), 1010 (2018). https://doi.org/10.1504/IJNT.2018.099938
17. Wei, X., et al.: A piezoelectric power generator based on axisymmetrically distributed PVDF array for two-dimension vibration energy harvesting and direction sensing. Sustain. Energy Technol. Assess. **44**, 101001 (April 2021). https://doi.org/10.1016/j.seta.2021.101001

18. Shen, D., Choe, S.-Y., Kim, D.-J.: Analysis of piezoelectric materials for energy harvesting devices under high- $g$ vibrations. Jpn. J. Appl. Phys. **46**(10A), 6755–6760 (October 2007). https://doi.org/10.1143/JJAP.46.6755
19. Melroy, G., et al.: PZT based active microfluidic droplet generator for lab-on-a-chip devices. In: Scholz, S.G., Howlett, R.J., Setchi, R. (eds.) Sustainable Design and Manufacturing, vol. 262, pp. 277–289. Springer Singapore, Singapore (2022). https://doi.org/10.1007/978-981-16-6128-0_27

# Collaborative Human-Robot Assembly: Methodology, Simulation and Industrial Validation

Junshen Chen, Abdullah Mohammed(✉), Theocharis Alexopoulos, and Rossitza Setchi

School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
alhusinalkhdurag@cardiff.ac.uk

**Abstract.** This paper developed an approach to integrate a human-robot collaborative assembly with a manual production line. The integration was completed effectively by exploring several collaboration algorithms. The study was conducted to enhance the working environment by improving the productivity and the quality of the production. Variability in the assembly processes was reduced, thus improving product quality and reducing rejects and reworks. The automation or robot collaboration was evaluated on one of the existing assembly lines, to help worker reduce repetitive work and increase productivity, which will also help to save labor costs over the long term. The inspection outputs from a robot are easily accessible, providing the quantitative data, analysis of which will lead to continual improvement.

**Keywords:** Collaborative robot · Industrial application · Robot assembly

## 1 Introduction

Robots have blended into humans' lives for several decades to assist humans in a large number of application areas. Recent years have seen new developments in human–robot co-assembly operations across the manufacturing sector. Global competitors and technological advancements have resulted in the use of such systems in more challenging and complicated manufacturing environments [1]. At the same time, a hybrid assembly task that combines a robot-assisted system with the human worker [2] has numerous vital and outstanding advantages, which substantially lessen the amount of fixed production costs in comparison to variable costs. Collaborative robotics triggered a huge shift from the traditional robot-in-a-cage model to robots interacting with people in a fenceless environment [3]. Consequently, human–robot collaboration is getting increasing attention in manufacturing applications. The cooperation of humans and robots in collaborative assembly tasks can take advantage of the differing strengths from both sides [4]. Generally, the robot provides several benefits including reduced worker fatigue and increased productivity. Human-robot collaboration therefore results in reduced levels of physical strains for human partners [5] while the human partner provides an incomparable ability


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 181–190, 2023.
https://doi.org/10.1007/978-981-19-9205-6_17

to operate high accuracy sensory components, and rapidly adapt to new and complex subtasks.

The conventional coding approaches for the collaborative robots are gradually becoming less able to satisfy the flexibility and variability of product developments, especially those with more personalized and customized requirements [6]. As a result, more efficient and rapid programming approaches need to be developed to enable the robot to be quickly adapted for new tasks in human–robot collaboration.

Programming by demonstration (PbD) is a similar technique to the record and replay technique, in which a robot is shown a set of movements and then repeats them exactly multiple times, but PbD has an aspect of learning integrated into it, making it a more effective system. In contrast to conventional coding procedure, PbD allows this process to be streamlined by showing the robot its task, while its position, joint rotations and any other required pieces of data are recorded. This allows it to repeat the task by following this data and no coding is required. It is also possible for the robot to learn how to deal with varying circumstances by showing it through multiple different but similar scenarios, enabling the robot to generalize its task. For example, Cousins et al. (2017) demonstrated the possibility of replicating the movement of the user's hands with robot's hands, allowing the robot to be adjusted remotely [7]. Wang et al. (2018) developed a teaching-learning-collaboration (TLC) model for the collaborative robot to learn from human demonstrations and assist its human partner in shared working situations [8].

During the last decade, the emergence of asset digitalization has enhanced the development of robot processes with simulation tools that can accurately represent the human-robot setup [9]. The work of Pieska et al. (2018) tests a number of modern robot process development tools where a simulation environment is used together with robot teaching or high-level programming to program the robot offline. Then the high-level code is translated to a low-level code that the robots understand and execute [10].

Cobots are inherently passive robots whose goal is to facilitate a full collaboration between the human and the robot. This collaboration means that the human and the robot will share the working envelope, the task and the process. This work presents the method followed to introduce cobots in the assembly process of a brake booster. The aim is to develop and validate an environment of a human-robot collaborative assembly. In such an environment the human and robot will work in cooperative mode where they will share the working space and the time. In more detail, 1) Introduce a system using cobots to assemble parts at production rates equal to or higher than the current ones. 2) Increase worker productivity during the assembly of two pistons, two extensions and two plungers. 3) Reduce repetitive work undertaken by workers 4) Minimize the effort to reconfigure the system for different parts 5) Design the system taking health and safety standards into consideration. 6) Achieve the results without the need for part tracing/identification.

The developed system is explained in the second section of this paper followed by the third section which describes the methods used in the approach. The fourth section illustrates the research results, and the final section presents the conclusions.

## 2 Methodology

To determine the type of human-robot collaboration, the distribution of tasks and the sequence of the distributed tasks follow a three-stages process. Firstly, the manual tasks are analyzed. Then, a simulation model that includes both the human and the robot is developed. The aim of the simulation model is to optimize the independent and collaborative activities as well as to ensure that the ergonomics of the assembly cell allows for the execution of all tasks and does not impose increased or unnecessary strain to the human. Finally, the tasks are individually validated at the purpose-built test bed with the actual robot and the equipment and tools required for the assembly. More detail on each of these stages is provided in the next sub-sections.

### 2.1 Assembly Procedure Analysis

In this section, every step of the assembly procedure is analyzed to decide where to deploy the robot to handle certain tasks. The following is the details of the criteria that have been used:

- The complexity of achieving the task by the robot: This aspect is needed to evaluate the challenges that the system integrator can face during the installation and programming of the robotic system. The complexity at this point is analyzed from the robot perspective. This means that the nature of the task will play a major role in deciding the level of complexity as some tasks are easier to be performed by the human and vice versa.
- The complexity of robot control: This criterion analyses two aspects in the robot: the first one is the kinematics of the robotic arm, the second one is the low-level control of the robot's joints. This is needed to control the robot movement.
- Reliability of the robot deployment: This criterion is measured by looking at the output of the assembly and evaluate the quality for several cycles. This will give indication about the level of trust in implementing the robotic solution in the manual production line.
- Possibility to deploy the robot using the current system and equipment: This criterion analyses the status of the production line the identify the benefits of implementing the robot in the existing setup. This helps the company to evaluate the feasibility of using the robot from the environmental, ergonomic and economical perspectives.

A summary of human-robot co-assembly procedure analysis is given in Table 1. The subassembly breakdown is categorized into seven main operations. Green color is the prior operations to implement the robot. Orange colored operations need further investigation due to the constrains of using current assembly tools. Red operations are easier for human operators due to the time limit of this project.

### 2.2 Production Cell Simulation

A novelty of this research project is that after the assembly process analysis a hybrid development methodology is followed that combines simulation in parallel to actual robot testing in a purpose-built testbed. Core objectives of the simulation model are:

**Table 1.** Assembly procedure analysis

| Categorised operations | Human | Robot | Constrains with current system and equipment |
|---|---|---|---|
| Pick-up parts, Place to nest | Repetitive work. Requires pre-unload parts for convenience of latter operations | Reliable. Adding the robot can save time and efforts | Grasping point of each individual part needs to be identify |
| Place bullet over part | Need to switch between different sizes of bullet for different parts | Achievable. In this step, the robot will do a repetitive job with one program | Design extension to the current bullet for robot to use these current tools |
| Pick up O-rings/seals from container | This step can be done by a human operator to eliminate the robot control complexity | Achievable but complex with limited project time | May require advanced sorting machine |
| Pick up pusher, push O-ring/seals down into groove | Speed depends on the skill of workers | Achievable. In this step, the robot will do a repetitive job with one program | Design extension to the current pusher for robot to use these current tools |
| Pick up circlip | This step can be done by a human operator to eliminate the robot control complexity | Challenging for robots to pick up single item from jumbled tray | |
| Sizer parts | Repetitive work | Achievable. Can be repeated/extended to different size without extra efforts | The grasping point of the part need to be identified |
| Store parts | Repetitive work. Can be done without extra effort if last step is done by human | Reliable. Adding the robot can save time and efforts | The grasping point of the part need to be identified |

- Assist in the development of the control logic,
- Provide a robot cell visualisation to ensure that the available hardware can be integrated and that both human and robot tasks can be done efficiently
- Enable an iterative process where simulation results are embedded into the testbed and testbed results are embedded into the simulation model.

Due to the nature of the simulation required, Siemens Process Simulate software package was selected. This simulation package supports a detailed human and robot simulation as well as virtual robot controllers that can be programmed like the actual controllers allowing for code sharing and validation in both virtual and physical environments.

The first step for the simulation model development was to create a number of different hardware setups that were proposed after brainstorming. These models contained all hardware and tools that were either available or possible to build without any interactions considered since this was the base to define the system logic. Some of the project participants used CAD software to express their ideas so the parts could be easily imported into the simulation software package. Visualization is important to enable the engagement of non-technical people that can provide valuable insight about the goals of the change in the production.

After a generic setup of tools, equipment and human working space was defined, the system interactions (logic) were modelled. This step took into account the assembly procedure analysis in order to separate the tasks that are done by the robot and establish sequences and relations or checks between all tasks (human and robot).

Then an iterative process was initiated where a specific process setup and logic was modelled and the tasks whose result was not deterministic were flagged to be tested on a physical system. A characteristic example are the tasks that involved the pushing of washers or O-rings into the respective grooves. The simulation model cannot ensure that the end-result would comply with the quality standards and in addition new robotic tools were developed to achieve the desired result. In these cases, the task was developed and tested on the physical testbed and the results were then passed to the simulation model in the form of a 3D CAD model of the new tool when new tools were developed and in the form of robot programming code when a different task execution was required.

Finally, the simulation model was used to make the production cell more ergonomic in aspects such as easy reach of parts and tools by the human, minimization of the collaborative space to improve human safety, and development of an easy to follow routine for the human to reduce the required levels of focus. The simulation model cannot be developed without the testbed (described in Sect. 3.3), and it is not intended to provide an independent offline solution that would be downloaded to a production cell robot only at the end of the development process (as it would be done in idealized process development cases).

### 2.3 Task Validation Testbed

As explained in Sect. 3.2, not all tasks could be designed through the simulation model. Installing washers and O-rings accurately required a redesign of the tool (pusher) that pushed the washer/O-ring to the correct position. Then due to the bespoke nature of the solution, details such as pushing angles/forces/speeds, and optimum tool gripping position had to be defined through a trial and error process. To develop these tasks a modular testbed was built where all trials could run. Since cobots can be easily relocated the testbed was installed at a controlled space outside the production to ensure the safety of personnel working on other tasks and prevent obstructions in production that shopfloor trials may cause.

The testbed consists of a table where the robot or other equipment can be mounted on (at any position), the robot with its gripper, manual part conveyors and storage boxes or trays. The testbed can be easily reconfigured which is important especially in the initial stages of development where the orientation of equipment and even the flow direction of parts has not been decided.

Parallel development (simulation and testbed) requires that tasks are designed as modules with discrete input and output in both the physical and the digital worlds. Taking the fitting of a washer as an example, the task input is the positions and orientations of the robot, of the pusher, of the washer expansion bullet and of the washer itself before the task begins. The output is the positions and orientations at the end of the task. To simplify the development of the cell the robot joints have zero speed at the beginning and at the end of the task and the state of each model item remains the same (for example no changes in shape or temperature). In addition to the physical system parts the digital input is the active signal(s) before task starts and the digital output is the signals generated at the end of the task (as a result of the task). This modular approach facilitates the transition between the physical testbed and the simulation model and ultimately enables the development of the cell partially as a simulation model and partially as a physical model. In the washer fitting example, the simulation model was developed with a generic task representing the washer fitting. This task was then developed and executed at the testbed using the input from the simulation model. The results were measured (in terms of time, position and orientation) and finally transferred to the simulation model along with the robot program.

Overall, the testbed could be considered as an extension of the simulation model. The latter provides a more complete picture of the final production cell but it lacks the accurate measurements, the quality checks and reliability verification which can only be done at the testbed.

## 3 Case Study Demonstrations

### 3.1 System Description

The manual assembly cell produces master cylinders for automotive brakes which are twin boosted to reduce up to 90% of the required pedal effort. The parts that this work assembled with a human-robot collaboration are the pistons (0.165 kg), the extension pistons (0.120 kg) and the plungers (0.338 kg). Examples of the parts are shown in Fig. 1.

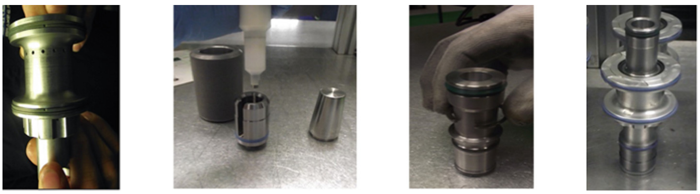


**Fig. 1.** From left to right: piston, piston extension, plunger, full assembly (piston tower)

Prior to assembling the parts, a number of seals and O-rings need to be mounted on the parts as well as a valve that is installed inside the piston extension. These form the biggest challenge either for the human that needs to follow precisely multiple steps or for the robot that must ensure that everything is mounted accurately.

The manual process that must be followed to prepare the piston, piston extension and the plunger is shown in Fig. 2. After the completion of Fig. 2 steps the three parts are ready to be installed in the cylinder. Since these are parts of a twin booster system a set of 2 pistons, 2 extensions and 2 plungers are needed for each booster assembly. Installation into the cylinders is done at a later stage and is not considered for the human-robot collaboration.

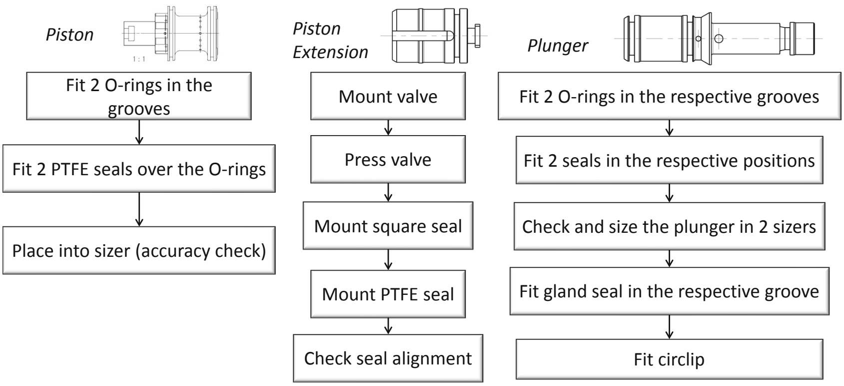



**Fig. 2.** Manual assembly steps

The average time needed for a skilled worker to assemble a piston, an extension piston and a plunger is 15 s, 40 s, and 45 s respectively. The total time for each twin booster is 200 s. Due to the nature of the manual work, there are numerous factors that can affect these times. However, the average was calculated by measuring the worker performance on one part and not on the average number of parts during a shift.

For the transformation of the assembly cell a Universal Robots (UR) UR5e robot [11] has been selected. UR robot is designed to make collaborative robot technology accessible to small and medium-sized businesses. UR5e is a 6-axis industrial manipulator with a weight of 20.6 kg, the maximal payload of 5 kg and a working radius of 850mm, featuring built-in torque/force sensors.

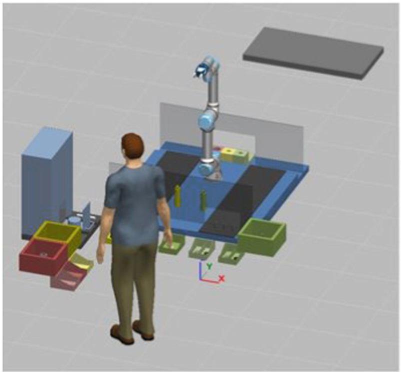
In manual control mode of the robot, the user can move each joint separately or move all joints synchronously by setting a goal position for the end-effector of the arm. A teaching mode is also available on the user's interface, which allows the user to move the arm by hand to the desired position.

The UR5e robot can run on automated control as well, and the programming can be performed at two levels, the Script Level and C-API Level. In case of Script Level programming, the arm is only controlled by a program written in URScript, a language developed by Universal Robots for the UR robot series. The URScript language is similar to Python programming language, and one can use variables, data types, functions and the flow of control statements. It also provides necessary commands for communication and motion control, but it does not include extended libraries for motion planning or advanced mathematics.

The grippers picked for this project are from SCHUNK, the Co-act EGP-C [12]. It is certified in accordance with ISO/TS 15066 and integrates easily and fast with the UR5e cobot.

## 3.2 Simulation Results

The first outcome of the simulation was the design of the human-robot collaboration cell. This is depicted in Fig. 3. All parts flow in the direction of the arrow shown in the figure. The human receives the trays containing the items to assemble, prepares the parts for the robot (which includes placing washers and O-rings over the respective expansion bullets) and operates the press that inserts a valve into the piston extension. Then the human places the parts in the respective designated areas and the robot finishes the assembly by pushing the washers and O-rings into the piston or plunger. Finally, the robot places the parts into a sizer and moves them to an area where the next worker can pick them up and continue the assembly process. All equipment and parts as well as the position of the human and the robot are placed in a way to minimize travelling distances. The human reaches assembly items and tools easily with minimum bending and the robot makes the most of non-collaborative areas where it can run at maximum speed and therefore reduce cycle times.



| Production Rate | 50 pistons, extensions, plungers per hour |
|---|---|

| Manual Operation | Time (sec) |
|---|---|
| Piston | 13.50 |
| Piston Extension | 29.89 |
| Plunger | 20.50 |
| **Total time** | **63.89** |

| Robot Operation | Time (sec) |
|---|---|
| Piston | 4.05 |
| Piston Extension | 24.74 |
| Plunger | 42.55 |
| **Total time** | **71.34** |

**Fig. 3.** Left: the simulated cell. Right: Simulation results

The second outcome of the simulation is the process logic. The robot operates in 'opportunistic' logic which selects between available tasks with a first in first out method. As soon as assembly items are available in the designated area the robot starts the task related to these parts. If parts are available in 2 different designated areas, then the robot carries on the task related to the parts that became available first.

The third outcome was the calculation of the collaborative process times. Figure 3 shows the summary of times for the groups of tasks carried out by the human (discussed in Sect. 4.2) and the robot. The robot is slower than the human and the overall cycle time equals the robot cycle time (72 s) which is 28% less than the cycle time of the manual process.

### 3.3 Testbed Results

The feasibility of the purposed robot-assisted assembly operations were tested and demonstrated on the testbed as shown in Fig. 4. Firstly, teaching by demonstration method was used in robot programming. This shortened the learning curve for the new operators and allowed them to use the graphical user interface (GUI) for programming the robot. This method also provides redundancy of manipulating other customized parts in different dimensions, which meets the needs of the company. This method was used throughout the development of the process to create the programs that were then passed to the simulation software.

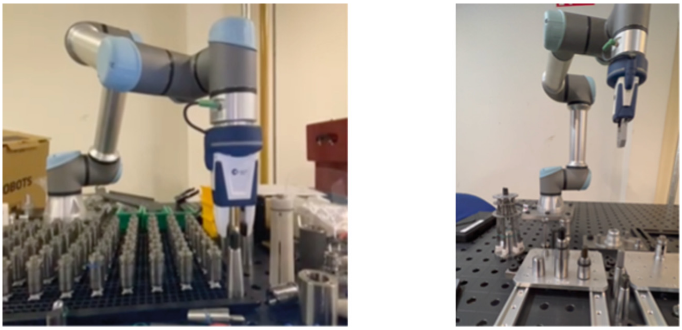


**Fig. 4.** Robot assembly tasks validation. Left: Piston extension. Right: Plunger

As mentioned in Sect. 3.3, a new type of pusher was designed to improve the efficiency of robot operation of installing O-rings and seals. Additional adapters handles and stands were also designed and used for robot gripper to interact with different tools. All these parts were tested in terms of finishing quality and process reliability.

## 4 Discussion and Conclusions

One of the main key findings that has been demonstrated in the reported research is the feasibility of introducing a collaborative robot to a manual assembly process. This is achieved by developing a hybrid model in which the robot and the shopfloor operator are working side by side. For the development, a novel approach is followed where a simulation environment and a physical testbed are running in parallel and provide feedback to each other. It is found that the introduction of the collaborative robot improved the productivity compared with the manual setup. Furthermore, the integration time for the collaborative robots was relatively short since they came with integrated safety sensors which limit the need for external safety considerations.

Two main challenges have been identified during the development of the approach, The first one is that the approach need to guarantee the safety of the operator working side by side with the robot. The second challenges are to find the balance between the speed of the operator compared with the robot as they need different times to perform the same task.

**Acknowledgements.** This work has been supported by the ASTUTE2020 (Advanced Sustainable Manufacturing Technologies) operation, which assists manufacturing companies across Wales, and has been part-funded by the European Regional Development Fund through the Welsh Government and the participating Higher Education Institutions.

## References

1. Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., Chryssolouris, G.: Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach. CIRP J. Manuf. Sci. Technol. **2**(2), 81–91 (2010)
2. Helms, E., Schraft, R. D., Hagele, M. rob@ work: Robot assistant in industrial environments. In: Proceedings. 11th IEEE International Workshop on Robot and Human Interactive Communication, pp. 399–404. IEEE (2002, September)
3. Wang, W., Li, R., Chen, Y., Jia, Y.: Human intention prediction in human-robot collaborative tasks. In: Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction, pp. 279–280 (2018, March)
4. Kru¨ger, J., Bernhardt, R., Surdilovic, D., Spur, G. Intelligent assist systems for flexible assembly. CIRP Annals **55**(1), 29–32 (2006)
5. Surdilovic, D., Radojicic, J.: Robust control of interaction with haptic interfaces. In: Proceedings 2007 IEEE International Conference on Robotics and Automation, pp. 3237–3244. IEEE (2007, April)
6. Pires, J.N.: New challenges for industrial robotic cell programming. Ind. Robot.: Int. J. (2009)
7. Cousins, M., Yang, C., Chen, J., He, W., Ju, Z.: Development of a mixed reality based interface for human robot interaction. In: 2017 International Conference on Machine Learning and Cybernetics (ICMLC), Vol. 1, pp. 27–34. IEEE (2017, July)
8. Wang, W., Li, R., Chen, Y., Diekel, Z.M., Jia, Y.: Facilitating human–robot collaborative tasks by teaching-learning-collaboration from human demonstrations. IEEE Trans. Autom. Sci. Eng. **16**(2), 640–653 (2018)
9. Thomas, A., Guerra-Zubiaga, D.A., Cohran, J.: Digital factory: simulation enhancing production and engineering process. In: ASME International Mechanical Engineering Congress and Exposition, Vol. 52019. American Society of Mechanical Engineers (2018)
10. Pieskä, S., Kaarela, J., Mäkelä, J.: Simulation and programming experiences of collaborative robots for small-scale manufacturing. In: 2018 2nd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS). IEEE (2018)
11. UR5e robot. https://www.universal-robots.com/products/ur5-robot/ Accessed 14/04/2022
12. Schunk Co-act EGP-C gripper. https://schunk.com/gb_en/gripping-systems/series/co-act-egp-c/ Accessed 14/04/2022

# An Adaptive Water Consumption Monitoring and Conservation System

Theocharis Alexopoulos[1](✉), Jacqueline Marsh[1], Gareth Llewellyn[2], and Michael Packianather[1]

[1] Cardiff School of Engineering, Cardiff University, 14-17 The Parade, Cardiff CF243AA, UK
alexopoulost@cardiff.ac.uk

[2] Pro-Flow Solutions Ltd., 36 Commercial Street, Tredegar NP223DJ, UK

**Abstract.** With the emergence of IoT, smart water monitoring systems have become widely available. Their operation is typically related to the detection of leaks and to water supply network management. These systems collect a large amount of data that can be used in new ways to improve current services and to introduce new functionalities for the user's health and safety. This paper is reporting the findings of a research project that developed a state-of-the-art water monitoring system and explored new ways to use the generated data and the system's capabilities. The project found that by grouping water consumption data into hourly intervals improves user understanding and provides enough detail to identify usage patterns. In addition, exploitation of the unique characteristics of the pipeline that was used for trials led to the development of a new small-leak detection method. The work expands system's application to user health and safety and proposes two more applications with their respective algorithms. The first application produces early notifications when people who live alone stop doing basic water consuming tasks and potentially require health assistance. The second application monitors and prevents the growth of Legionella in the water supply system.

**Keywords:** Smart water monitoring · Leakage detection · Legionella control

## 1 Introduction

Water conservation is important for long term preservation of fresh water resources and also to reduce the costs for water companies, consumers and insurance companies. In fact, insurance companies in the UK pay £1.8 million every day on property damages related to water leaks [1]. In this regard, internet of things (IoT) solutions are being used to collect and analyse data with a focus on minimising the amount of water lost through leaks. However, domestic and commercial water consumption data contains much more value, and the following sections present how this can be utilized in a wider range of applications which include the observation of changes in consumer habits, the protection from pathogens and the increase of water supply availability.

Due to its potential for cost reduction, the development and application of water consumption monitoring, has been explored especially during the last decade initially


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 191–200, 2023.
https://doi.org/10.1007/978-981-19-9205-6_18

from a water supplier's perspective and later from a consumer's perspective. In a 2008 publication Britton et al. [2] reported the results of a pilot study in Hervey Bay Australia where the water meter readings of 2,359 residential properties were recorded. Among other findings, the study identified residential properties where water leaks of more than 1 L per hour were present. To identify the leaks the water consumption between 1am and 4am was analysed and if the water flow during this time was constant the property was visited by a plumber who located and repaired the leak. The method, which is typically referred as minimum night flow (MNF), correctly identified the leak in 52 out of 54 cases. To simplify the monitoring system installation Larson et al. [3] developed a system based on single point water pressure measurement and used the system to survey household consumption. Using fluid dynamics theory, they created different profiles for each type of water usage by mapping the pressure drop to the activity that was taking place.

In the following years, improvements in microcontrollers, small size computers and wireless technology created a commonly accepted way that water consumption is monitored. A flow meter is installed at key points of a pipeline and through a microcontroller the readings are sent wirelessly to a computer or directly to cloud-based services. There the data is stored and graphical user interfaces provide insight to the users about their water consumption and the current state of the system. In addition, the collected data is analysed, and notifications are generated to warn about potential leaks or excessive consumption. Indicative works following this approach are [4–7] and the same approach is followed by the majority of off the shelf solutions which operate similarly to the product examples discussed later in this report [12, 13].

The aim of the majority of studies about water consumption monitoring is primarily to detect water leaks and to assist in water supply management. Aziz et al. [8] combined IoT with a geographic information system (GIS) technologies to monitor water consumption at Universiti Teknologi Malaysia campus. The system combines data from various monitoring points around the campus to provide a real time digital model of the campus and to manage the drop in pressure in different parts of the site. In another research project, Farah and Shahrour [9] developed a system that monitors the water distribution and consumption at Scientific Campus of Lille University France. The system analyses monitoring data of a 15km pipeline to spot leaks with an adapted MNF method. The campus does not have zero flows during the night, so the method uses a probabilistic approach to classify the monitored flows based on the risk of leak.

The increasing number of water monitoring applications has created demand for higher levels of accuracy in locating leaks and in providing system autonomy that enables monitoring in places that power supply is not available. Abate et al. in [10] provide a review of the leak detection methods and compare the advantages and disadvantages of various sensing technologies. They also propose a battery supported system of very low energy consumption to achieve an autonomous operation for more than 3.5 years. In a recent work, Pietrosanto et al. [11] demonstrate the need for higher accuracy of flow sensors. As they explain, despite the improvements in terms of real time data collection and analysis, a small leak is not detected by flow meters that conform to the current standards.

To complete the review of previous work, it should be noted that currently there are numerous products available that monitor water flow, inform the user over the internet for identified leaks (based on the aforementioned methods) or excessive consumption and can switch off water supply. Two of the more advanced solutions are Flo [12] which offers the above functions with modern ways of connectivity and LeakBot [13] that excels in installation simplicity since it does not require any modifications of the pipeline. A key incentive for buying these products is the reduction in building insurance premium but as Pietrosanto et al. explain in [11] a new generation of systems is required for safer and more accurate water monitoring.

The reviewed studies and applications are limited to major leak prevention and usage statistics from a water supply point of view. However, there is potential to improve leak detection and to introduce new applications of water consumption monitoring beyond water conservation. This work developed a water flow monitoring system to analyse data from a user's perspective, explore ways to overcome sensor limitations and identify new ways to extract value from the datasets and improve users' health and safety.

The rest of this paper is structured as follows. Chapter 2 presents the system setup and the way that data is recorded and forwarded to the computer that stores and analyses the data. Chapter 3 presents the findings from data analysis together with the suggested methods for small leak detection and user safety enhancement.

## 2 The Developed Water Flow System

To experiment with the data collection and analysis a water flow monitoring system was developed and built using the practices reviewed in the previous section [4–7, 12, 13] as a starting point. The system hardware can be adapted by adding new sensors of a different model or even type. The analysis and control software is parameterised and can be updated with new decision algorithms. The system parts are:

- Hall effect flow sensor. The sensor's range is 1–30 L/min and its output is a square signal (pulses) that indicate the volume of the water passing through it. (Fig. 1B)
- Thermometer embedded to the housing of the flow sensor (custom built Fig. 1B).
- ASCO-Sirai L182D2 solenoid valve that works with a 12 V power supply Fig. 1C
- NodeMCU - ESP8266 based microcontroller (Fig. 1A)
- Raspberry Pi 3B + with official 7 inches touchscreen case (Fig. 2)
- 10 kΩ resistor, 5 V voltage regulator, IRF540N metal-oxide-semiconductor field-effect transistor (MOSFET) and 12 V power supply to power the monitoring system and switch the sensors and valve on or off. (Fig. 2 and Fig. 3)

The flow meter and thermometer are connected to the microcontroller which translates the signals to values whose units are litres and Celsius degrees respectively. The microcontroller generates a data sample every 10 s and sends the sample to the server (running on the Raspberry Pi) using a WebSocket protocol. In parallel to the data acquisition system, a web application is running on the server which provides a graphical user interface showing latest measurements and data statistics. Communication with the microcontroller is bidirectional so that through the webapp the user can switch the valve

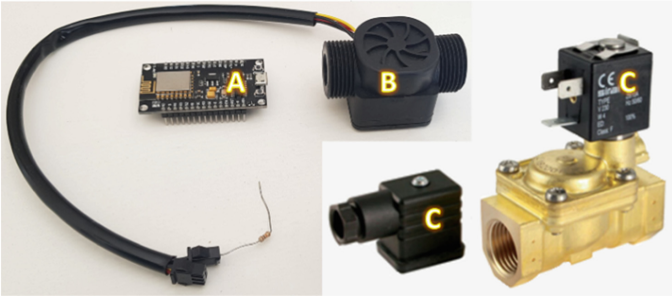



**Fig. 1.** A. Microcontroller, B. Flow meter, C. Solenoid valve with plug


**Fig. 2.** Assembled system. Left flow sensor setup. Right Raspberry Pi setup.

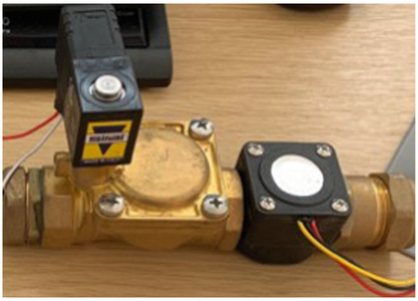


**Fig. 3.** Valve and flow sensor assembly as installed to the water mains.

on/off either manually or by using an algorithm that defines the conditions under which the valve should shut off the water supply. The software that was used to build the system is:

- Apache Tomcat webserver. Hosts the web application and the application programming interface that enables the microcontrollers to connect, submit data and receive commands.

- Arduino, ESP8266WiFi and WebSocket libraries. These are required to develop the firmware for the microcontroller
- MariaDB relational database server. This is where the collected data and analysis results are being stored. During the system development the database was running on the Raspberry Pi but then it was moved to a cloud service.

Due to the system design, multiple flow sensors can be installed at different points so consumption in different parts of the pipeline can be monitored. To add a new sensor, the microcontroller firmware is installed on the microcontroller and each microcontroller uses its MAC address as identification to register itself to the server and send the collected data. Apache Tomcat server can support up to 200 connections, but it has not been tested whether the hardware hosting the server was powerful enough to support a network of 200 sensors. The system was initially calibrated by connecting the flow meter to a tap and filling up 10 L containers. The amount of signal pulses was recorded so the exact number of signal pulses per litre that passes through the sensor could be calculated. The setup was also used to identify the maximum flow rate that does not move the sensor's turbine and therefore passes unidentified (meaning a steady flow value of 0 pulses).

After the development phase, the system was installed at a residential property, and it collected data for 5 months from the property's water mains. During that time the system was protecting the property from leaks or pipe bursts. Since the 5-month trial did not capture any actual leaks, the setup was also tested in a second residential property to monitor the pipeline of a bathroom, but this setup was only used to test consumption profiles and experiment with different water flow cases.

## 3 Application and Findings

The research project that this work is part of explored various aspects of water flow monitoring and consumption and therefore multiple observations were recorded and are being reported. The contribution of this work is split in two parts. Firstly, it deals with gaps in the literature by proposing an efficient way to store and visualise consumption data and introducing a new method to identify small leaks. Then the second part is about a new way to use the system and generate more value out of it without the requirement for additional hardware. Chapter 3 is split into 4 sections each of which represent a separate contribution.

### 3.1 Data Visualisation

The 5-month trial generated about 1.2 million samples of data which in its raw format is not usable by the system user. In addition, raw data has the typical issues of noise and of extreme values due to sensor malfunctions. The system was recording a sample every 10 s and initially, an average of 3 samples proved to be adequate in terms of smoothing out noise and absorbing the extreme values. However, to make the data usable and to facilitate the understanding of underlying patterns different groupings of data were examined. The user of the system was also interviewed in order to identify the best data visualisation method.

After analysing the characteristics of each data grouping the 1-h interval was selected as the system's default. In Table 1 a brief description of the findings from testing different intervals is presented.

**Table 1.** Findings for different data grouping intervals

| Interval (mins) | Findings |
|---|---|
| <30 | Noisy data which due to zero consumption gaps it does not reflect of high-low water consumption. Patterns are not recognisable. High consumption events are clearly visible |
| 30–120 | Smooth data, indicating intervals with high consumption events. Daily patterns are easily identifiable and the user can relate the data to their schedule |
| >120 | Smooth but underlying usage patterns are non-identifiable. High consumption events are smoothened out completely |

Finally, the selected method processes the data in two steps. First the cumulative value of water volume consumed each hour of the day is calculated and stored in a separate dataset. Then, from the new dataset, the average value of the hourly consumption is calculated, and a chart is produced to visualise the results. Regarding temperature, the hourly values in both steps represent the average temperature during that hour. Figure 4 shows the generated charts for the 5-month trial.

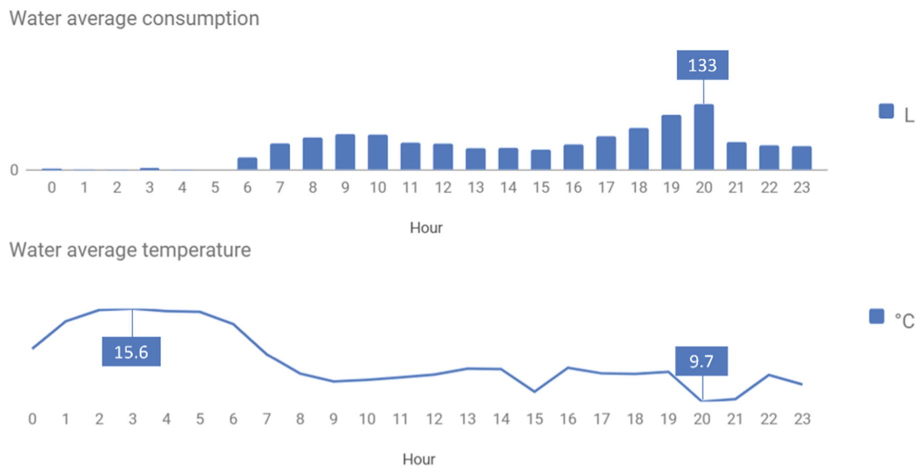



**Fig. 4.** Average recorded values during the trial period

### 3.2 Small Leak Detection

As discussed in the introduction, the vast majority of studies and off the shelf products identify leaks by spotting continuous flow during times where no flow is expected (typically during early hours). The problem with this approach is that small leaks are not detectable as the flow meters have a minimum in the range that they can measure. The flow meter of the system described in Chapter 2 has a minimum range of 1 L per hour. The sensor was tested at lower flows by filling 10 L containers mounted on a 1 g precision scale at decreasing flows. It was found that the flow meter continues to measure flows under the rated minimum flow, but the accuracy drops as the flow is reduced. Finally, the flow meter was not able to detect a flow of 0.45L/h and it would not start measuring again unless the flow was not exceeding the 0.6L/h threshold.

To overcome the limitations of the flow meter, this work proposes the use of the physical characteristics of the pipeline to identify the leak. To achieve this, the valve shuts off and therefore the pipeline is isolated from any supply of water. If a leak exists, then the water will continue leaking until the pressure inside the pipeline drops to a level that is not enough to push water outside the gap/hole. As soon as the valve is switched on again the portion of water that exited the pipeline will be substituted almost instantly causing a spike in the metered flow value. To detect the spike, the system checks the value of the first water flow sample collected after the valve is open. If it is more than a set value ($>1$ pulses) then a warning for potential leak is shown to the user. Although the leak detection process can be automated by running multiple tests during low consumption times the pilot system does not automatically shut off the supply. A manual confirmation by the user is required until further testing ensures that the probability of a tap being open during all automatic tests is zero.

For this method to succeed a combination of the following phenomena should occur. The first (and most effective) is that the leak is not at the highest point of the pipeline and therefore the hydrostatic pressure of water will maintain enough pressure to enable the continuation of leaking. A secondary phenomenon is the increase of the capacity of the pipeline under pressure at least as much as the flow meter can measure. This would typically happen due to the air that is in the water or that is trapped within the pipes which, contrary to the water, is compressible and will reduce its volume under pressure. If a leak exists, the air decompresses and continues to apply the required pressure to maintain the leak. For reference, the flow meter produces a pulse for every 5.7mL of water which indicates the portion of leaked water that can be detectable.

These observations are based on the deployed system. If the only aim of the system is leak detection, then it is suggested that a pressure sensor is installed after the valve which would detect the pressure drop much more accurately. However, this work did not produce pressure related data to allow for further discussion of this solution. It should also be noted that other flow meters may be able to detect lower levels of flow compared to the one used for the reported research work but as it was found in [11] the flowmeters complying to the current standards could allow water leaks of several litres to remain undetected during a day. This may not be enough to cause a flood, but it can damage woodwork or lead to mould growth inside walls or other hidden parts of a building.

### 3.3 Person Activity Monitoring

The initial aim of the research project was to find new ways to use the data that the system produces. Figure 4 demonstrates that a household has a usage pattern, but further data analysis shows that specific water consumption events can be detected and lead to conclusions about the state of the people that live in the house. In the case of houses that only one person lives in, the absence of water consumption events means either that the person is not home or that the person is not able to do the tasks that require water consumption. A typical task would be flushing the toilet which when it happens it is an indication that the person can to move around the house and do basic tasks.

To examine whether it is possible to detect separate events the raw data was analysed to see if specific water consuming activities are detectable. To facilitate the investigation, typical tasks involving the usage of the bathroom, using washing machines and food preparation were examined independently. The first finding is that tasks that consume water through an automated mechanism create a consistent consumption profile. Figure 5 shows the consumption profile of flushing the toilet and on the same chart the consumption profile of handwashing that would typically take place afterwards is shown. The second finding is that automated mechanisms tend to use the maximum supply capacity which makes it easier to detect the profiles due to a clear difference from multiple manual tasks that consume water at low flow rates.

The combination of the above findings with knowledge about water consumption related to physical needs of the person that lives in the house led to the selection of cistern refill as an ideal water consumption profile to seek for. Multiple recordings led to the creation of an 'average' profile that is naturally combined with handwashing.

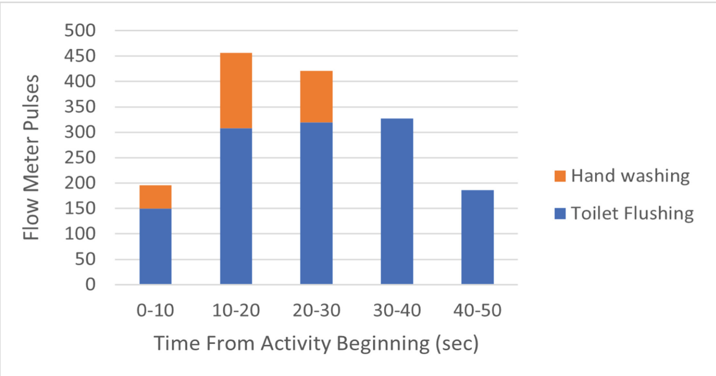



**Fig. 5.** Consumption profile of common water consuming tasks.

Toilet flushing is detected by the installed system if: A, flow rate exceeds 300 pulses per 10 s for at least 3 consecutive samples (meaning 30secs) and B, the total number of pulses through a period of 50 s is at least 1200. A is related to the maximum flow that the cistern's refill mechanism allows (assuming a constant pipeline pressure) and B is related to cistern's capacity. Both criteria are unique for each cistern and therefore detection algorithm parameters require initialisation for every new setup.

In addition to the consumption type selection, it was also found that increasing the sampling rate to 1 Hz provided a better distinction between overlapping consumption profiles. This is due to many tasks taking only a few seconds to complete and therefore requiring higher resolution to create noticeable patterns. In any case, the goal is to ensure that the person that lives in the house is active and therefore false detections are still a sign of activity. If no activity is detected the system will raise a flag on its dashboard and the care service responsible for the person will take actions such as calling the person or visiting the house.

### 3.4 Prevention of Pathogens

Faucets, shower heads and generally water systems where water remains stagnant for prolonged periods can potentially support Legionella bacterial growth. The developed system monitors both the flow and the temperature of the water which are factors that determine if the environment is favourable for the growth and multiplication of the bacteria. According to the World Health Organisation Legionella bacteria multiply at temperatures over 25 °C and it is recommended that the water does not remain stagnant for more than a week even if the temperature is below 25 °C [14]. To prevent legionellosis the water systems should be treated with disinfectants or flushed.

There are many more factors affecting Legionella growth but controlling water flow and temperature can eliminate the dangers. A notification module had been implemented into the monitoring system which flags a monitoring point as susceptible to Legionella growth if no flow has been recorded for a week. The system produces the same warning if the temperature of the water is over 25 °C A major limitation of the system is that it cannot ensure that the risk is eliminated unless a sensor is installed at every point where water exits the pipeline. The latter is not practical for residential applications, but it can be a viable solution for hotels or hospitals where personnel must ensure that faucets and showerheads are regularly flushed. Combined with electric valves the system can automatically send a signal to turn on and flush the faucets or showerheads that have not been used for a week.

## 4 Conclusion

Water monitoring systems have evolved during the last decades and are capable of real time collection and processing of water consumption data. This facilitated the quick identification of major water leaks and assisted water suppliers in managing their networks. Further utilising the capabilities of these systems will increase user engagement through better data visualisation methods. By introducing small leak detection algorithms and by exploiting the physical characteristics of the water supply pipelines the detection of small leaks will be possible even with sensors that are currently not sensitive enough to spot them. In addition, new algorithms related to user health and safety can assist in the development of warning systems that send notifications when a person who lives alone stops doing common daily tasks or when a water supply system is susceptible to Legionella growth. There is however a need for further investigation of the patterns, algorithms and methods that can identify specific water consumption activity and therefore automate the proposed system's health and safety functionalities. Especially about legionella prevention, this work has to be combined with studies testing different pipelines and appliances to enable the development of a system that can autonomously ensure that legionella standards are followed.

**Acknowledgements.** *Acknowledgements:* This work has been supported by the ASTUTE2020 (Advanced Sustainable Manufacturing Technologies) operation, which assists manufacturing companies across Wales, and has been part-funded by the European Regional Development Fund through the Welsh Government and the participating Higher Education Institutions.

## References

1. Association of British Insurers, https://www.abi.org.uk/products-and-issues/choosing-the-right-insurance/home-insurance/burst-pipes-and-water-leaks, last accessed 2022/05/07
2. Britton, T., Cole, G., Stewart, R., Wiskar, D.: Remote diagnosis of leakage in residential households. J. Aust. Water Assoc. **35**(6), 89–93 (2008)
3. Larson, E., Froehlich, J., Campbell, T., Haggerty, C., Atlas, L., Fogarty, J., Patel, S.N.: Disaggregated water sensing from a single, pressure-based sensor: An extended analysis of HydroSense using staged experiments. Pervasive Mob. Comput. **8**(1), 82–102 (2012)
4. Gosavi, G., Gawde, G., Gosavi, G.: Smart water flow monitoring and forecasting system. In: 2017 2nd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT), pp. 1218–1222 (2017)
5. Fikejz, J., Roleček, J.: Proposal of a smart water meter for detecting sudden water leakage. In: 2018 ELEKTRO, pp. 1–4 (2018)
6. Teixidó, P., Gómez-Galán, J.A., Gómez-Bravo, F., Sánchez-Rodríguez, T., Alcina, J., Aponte, J.: Low-power low-cost wireless flood sensor for smart home systems. Sensors **18**(11), 3817 (2018)
7. Farah, E., Shahrour, I.: Smart water for leakage detection: Feedback about the use of automated meter reading technology. In: 2017 Sensors Networks Smart and Emerging Technologies (SENSET), pp. 1–4 (2017)
8. Aziz, N.A., Musa, T.A., Musliman, I.A., Omar, A.H., Aris, W.W.: Smart water network monitoring: a case study at Universiti Teknologi Malaysia. Int. Arch. Photogramm., Remote. Sens. Spat. Inf. Sci. **46**, 3–7 (2022)
9. Farah, E., Shahrour, I.: Smart water technology for leakage detection: feedback of large-scale experimentation. Analog Integr. Circ. Sig. Process **96**(2), 235–242 (2018). https://doi.org/10.1007/s10470-018-1137-1
10. Abate, F., Carratù, M., Liguori, C., Pietrosanto, A.: Smart meters and water leakage detection: A preliminary study. In: 2019 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 1–6. IEEE (20 May 2019)
11. Pietrosanto, A., Carratù, M., Liguori, C.: Sensitivity of water meters to small leakage. Measurement **15**(168), 108479 (2021)
12. MOEN Homepage, https://www.moen.com/flo, last accessed 2022/05/07
13. LeakBot Homepage, https://leakbot.io/, last accessed 2022/05/07
14. Bartram, J., Chartier, Y., Lee, J.V., Pond, K., Surman-Lee, S.: Legionella and the prevention of legionellosis. World Health Organization (2007)

# Comparative Analysis of Virgin and Recycled ABS Filaments

Raquel Sudbrack(✉), Gabriela Cerveira, Greice Caldovino, Luis Henrique Cândido, and Fabio P. Silva

Federal University of Rio Grande do Sul, PGDesign, Porto Alegre - RS, Brazil
raquelsudbrack@gmail.com

**Abstract.** This paper aims to conduct a comparative analysis between commercially available virgin and recycled ABS filaments of parts printed by Fused Filament Fabrication (FFF) technology as well as to provide information on the differences in performance of both materials for 3D printing. Material characterization methods (FTIR, TGA, DSC and DMA), FFF for the manufacture of specimens and mechanical tensile and impact tests were used to determine the characteristics of each printed material. The study showed small differences in composition and mechanical behavior between the two materials. The main finding was that Virgin ABS had higher impact resistance. In addition, the recycled material behaved more unstable during the 3D printing process. The results showed some differences between the two materials, virgin ABS proved to be much more resistant to impact. In addition, recycled ABS displayed a little more sensitive behavior to temperature and humidity when compared to virgin ABS.

**Keywords:** 3D printing · Additive manufacturing · Fused Filament Fabrication · Acrylonitrile butadiene styrene · Recycled material

## 1 Introduction

Fused Filament Fabrication (FFF), also known as Fused Deposition Modelling (FDM), is the most widely used process among the manufacturing technologies available in 3D printing, according to Gomes-Gras et al. (2018). This technology allows for fast, small-scale, low-cost production of customized products without the need for machining or tooling (Berman 2012). Industry, educational institutions, and ordinary users have an increasing interest in 3D printing (Soares et al. 2018). The economic and environmental issues of this sector must be considered, as this technology is promoting a change in energy and material consumption, causing an unpredictable impact on society (Griffiths et al. 2016). Due to an improvement in additive manufacturing, technologies, and production speeds, it seems that the amount of 3D printed polymers will continue to increase (Lanzotti et al. 2019).

The orientation, direction and scanning style of the printing process can influence the mechanical properties of the manufactured part, and for this reason the characterization of the materials used contributes to the understanding of some limitations (Goh et al.


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 201–212, 2023.
https://doi.org/10.1007/978-981-19-9205-6_19

2017). There is little published data on the mechanical properties of parts manufactured by 3D printing from recycled filament (Anderson 2017). According to Balart et al. (2005), in order to enable the reuse of a recycled material it is extremely important to maintain an adequate stability between its properties and processability. Despite this, there is no need for the properties of the recycled material to be identical to those of the virgin material.

According to Anderson (2017), the parts produced from recycled PLA (Polylactic Acid) filament displayed a good performance, which encourages conducting new tests with other polymers, such as ABS (Acrylonitrile Butadiene Styrene). Currently, there are several filament options for 3D printing and an increasing demand for products made from recycled raw materials (Dul et al. 2016).

3D printing contributes to sustainable manufacturing through the possibility of using recycled materials and reducing waste, energy demand and carbon emissions (Nadagouda et al. 2020). In the present experimental study, ABS was used in this process, since it is one of the most common materials used in 3D printing. Thus, the objective of the present study was to conduct a comparative analysis between national commercial filaments of virgin and recycled ABS of 3D printing parts using FFF technology to determine their performance and to establish possible differences between them.

## 2 Experimental Study

The materials tested were two ABS filaments produced in Brazil by different manufacturers: the virgin ABS from Filamentos 3D Brasil (F3DB) and the recycled ABS from PrintGreen 3D. A black colored 1.75 mm 3D printing filament was selected for standardization purposes. According to their respective manufacturers, virgin ABS is generated from a resin that has a high fluidity index, while recycled ABS is created from automotive electronic casings. The comparative analysis between the filaments consisted of two phases: characterization of materials and mechanical tests, in which different techniques were used (see Fig. 1).

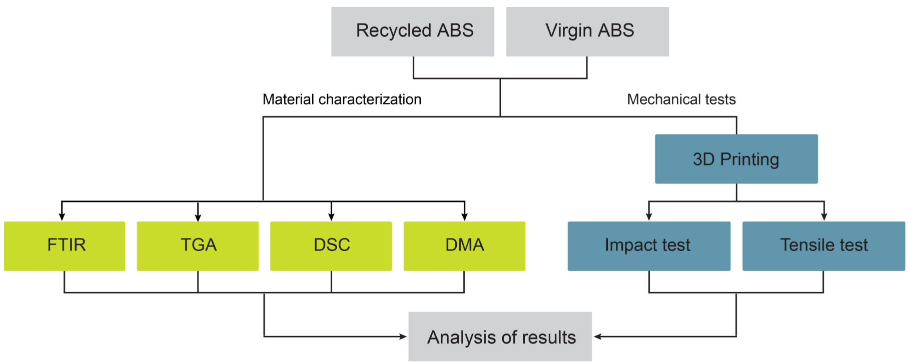



**Fig. 1.** Diagram of the methodological procedures.

Particulate Matter (PM) emission profiles are significantly impacted by print filament type, brand and color over time. During 3D printing, the filament brand can be responsible for relevant differences in the PM emission profiles. These differences occur because the type and loading of components within these filaments vary for different brands (Khaki et al. 2021).

## 2.1 Material Characterization

For a more comprehensive evaluation of the properties of the selected materials, both filaments were submitted to three techniques: Fourier transform infrared spectroscopy (FTIR); Thermogravimetric analysis (TGA); Differential scanning calorimetry (DSC).

The FTIR technique promotes the vibration of chemical bonds established between atoms due to energy absorption through the emission of infrared radiation in a sample. The evaluation of absorption spectra allows the characterization of the chemical composition of complex samples (Rubio et al. 2016). The equipment operated in this test was a PerkinElmer Spectrum 100 with resolution of 4 $cm^{-1}$, in which the surfaces of three samples of each material were analyzed by performing 16 scans per sample.

TGA is a thermal analysis technique that measures the amount and rate of change in the weight of a material as a function of temperature or time in a controlled atmosphere, and displays the process of material degradation (Divyathej et al. 2016). This analysis of the materials was performed using a TGA-Q50/TA device. The ABS filaments samples, weighing approximately 10 mg, were analyzed at a heating rate of 10 °C/min in a nitrogen atmosphere in the temperature range of 23–600 °C.

The DSC technique is used to measure the energy difference between a sample and a reference material as a function of a heating or cooling program under a controlled atmosphere (Denari and Cavalheiro 2012). In this study, the tests were performed using a NETZSCH DSC 404 F1 Pegasus® device (platinum crucible). At approximately 10 mg, the samples were heated once in the temperature range of 25 to 600 °C, with a heating rate of 10 °C/min in a nitrogen atmosphere.

## 2.2 Mechanical Tests

The mechanical tests were initiated with the 3D printing process for the production of specimens with virgin and recycled ABS filaments. Next, the specimens were used for the tensile and impact tests.

**Fused Filament Fabrication - FFF.** According to Kim et al. (2018), the design capability for part quality depends on the settings used for printing, such as layer thickness, fill pattern, print speed, among others. Therefore, the print definitions used in this study were: 50% infill (the maximum value allowed by the equipment); 0.1 mm layer height; 0.4 mm wall thickness (4 layers); XY building orientation at 45°; and no support material. All specimens were printed using a Cliever CL1 3D printer, with a 0.3 mm diameter nozzle. Table 1 shows the printing parameters considered suitable for the filaments, in order to obtain parts with good quality.

**Tensile Test.** According to Dizon et al. (2018), the tensile test allows the measurement of the material mechanical strength and the variation of this deformation due to the applied tension. In the present study, five samples of each material were tested. The equipment

**Table 1.** Printing parameters for the specimens.

| Parameters | Virgin ABS | Recycled ABS |
|---|---|---|
| Extruder nozzle temperature (°C) | 205 | 215 |
| Bed temperature (°C) | 100 | 110 |
| Density (g/cm$^3$) | 1.04 | 1.0 |

used was a Shimadzu universal testing machine, with a 5 kN maximum capacity and 5 mm/min speed.

Studies have shown results that included the final resistance, deformation and modulus of elasticity of the printed parts and described the interference of the printing parameters in their mechanical properties. Thus, the specimens were manufactured by means of 3D printing, following the ASTM D638-2A type IV standards.

**IZOD Impact Test.** The IZOD impact test determines the impact resistance of materials when submitted to a sudden force, determining the impact energy or energy absorbed before fracturing (Divyathej et al. 2016). Five samples of each material were tested using an Instron, CEAST 9050, 5.5 J pendulum-type hammer. Similar to the tensile test, the specimens were also manufactured by the FFF printing method, but followed the ASTM D256 standard instead.

A tensile concentrator, represented by a notch located in the middle of the specimens, with angle and indentation specified by the testing standard, was observed during 3D printing. According to Roberson et al. (2015), the differences between printed and carved notches on ready-made parts are not significant, suggesting that a printed notch is also appropriate for samples used in the impact test.

# 3 Results and Discussions

## 3.1 Fourier-Transform Infrared Spectroscopy

The resulting graphs showed a similarity in the main structural composition between virgin and recycled ABS (Fig. 2). These values were mainly due to the presence of three groups that characterize the material: the alkyl group made from a simple bond between carbon and hydrogen (C-H) at the peaks 3000–2800 cm$^{-1}$; the nitrile group made from a triple bond between carbon and nitrogen (C≡N) at 2237 cm$^{-1}$; and the presence of an aromatic compound at 1495 cm$^{-1}$ peak. Such information (Table 2) was obtained in the FTIR software and libraries and compared to that of Li et al. (2017).

However, significant differences were found between the two materials as shown in the following bands of the spectrum of recycled ABS: 1772.12 cm$^{-1}$, 1224.40 cm$^{-1}$, and 1162.44 cm$^{-1}$ (Fig. 2). According to Li et al. (2017), the bands investigated confirmed the presence of the carbonyl group around 1772 cm$^{-1}$ and a C-O bond stretching vibration of approximately 1200 cm$^{-1}$ can be observed, which characterizes a carbonate bond present in the PC (polycarbonate) molecule (Table 3). These aforementioned authors reported that the peaks at 2237 $cm^{-1}$, 1772 $cm^{-1}$, 965 $cm^{-1}$, and 910 $cm^{-1}$ represent a mixture composed of ABS and PC polymer.

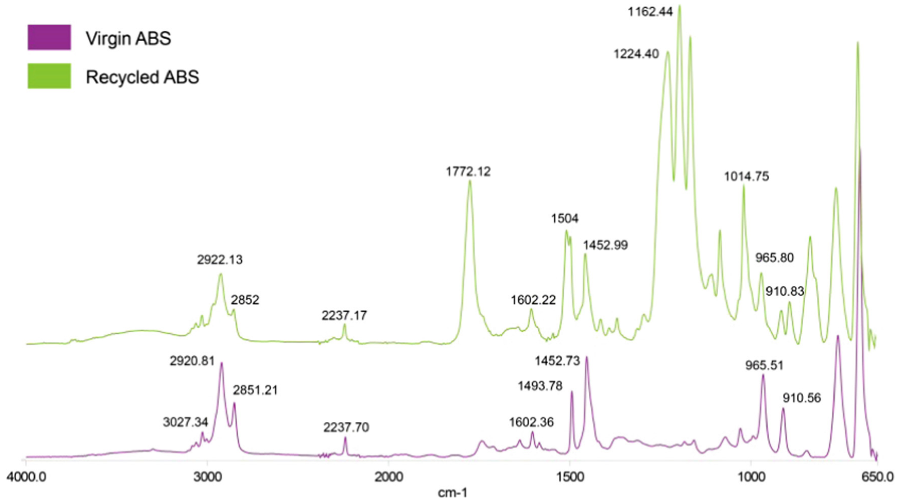



**Fig. 2.** FTIR spectrum of virgin ABS and recycled ABS filaments.

**Table 2.** Identification of FTIR bands ($cm^{-1}$) in ABS filaments.

| Virgin ABS | Recycled ABS | Reference* | Corresponding functional group* |
|---|---|---|---|
| 3027 | 3200–3000 | 3200–3000 | Stretching vibrations of aromatic |
| 2920–2851 | 2922–2852 | 3000–2800 | Stretching vibrations of aliphatic C—H |
| 2237 | 2237 | 2237 | Acrylonitrile unit represented by the C = N bond |
| 1602 | 1602 | 1638 | Stretching vibration of C = C double bond from butadiene units |
| 1493 | 1504 | 1495 | Stretching vibration of aromatic ring from styrene unit |
| 965 | 965 | 967 | Deformation of C—H for hydrogen atoms attached to alkane carbons for 1,4 butadiene units |
| 910 | 910 | 911 | Deformation of C—H for hydrogen atoms attached to alkane carbons for 1,2 butadiene units |

*Reference bands of functional groups according to Li et al. (2017).

Other authors have also attributed such FTIR spectra to ABS and PC blends from the automotive sector (Balart et al. 2005; Ferreira et al. 2018), which confirms the specifications provided by the manufacturer of the recycled filament. It can be concluded that, despite the presence of PC in the recycled material, both commercial filaments were mostly composed of acrylonitrile butadiene styrene.

**Table 3.** Identification of typical bands ($cm^{-1}$) of PC in recycled ABS filaments.

| Recycled ABS | Reference* | Corresponding functional group* |
|---|---|---|
| 1772 | 1772 | Typical carbonate bond with an infrared absorption of carbonyl group |
| 1224 | 1200 | Stretching vibration of C—O bond |
| 1162 | | |

*Reference bands of functional groups according to Li et al. (2017).

## 3.2 Thermogravimetric Analysis

The comparative analyses of the materials showed a quite similar behavior pattern between them. ABS degrades in two stages: Stage 1 with temperatures ranging from 180 to 480 °C, and Stage 2, from 480 °C to 620 °C (Yang et al. 2004). In both samples, the TGA curve (Fig. 3) exhibits a mass loss, confirming the required pattern of the material. However, a difference of 12.31 °C in the degradation temperature of the recycled ABS sample was identified, suggesting the presence of fillers and additives.

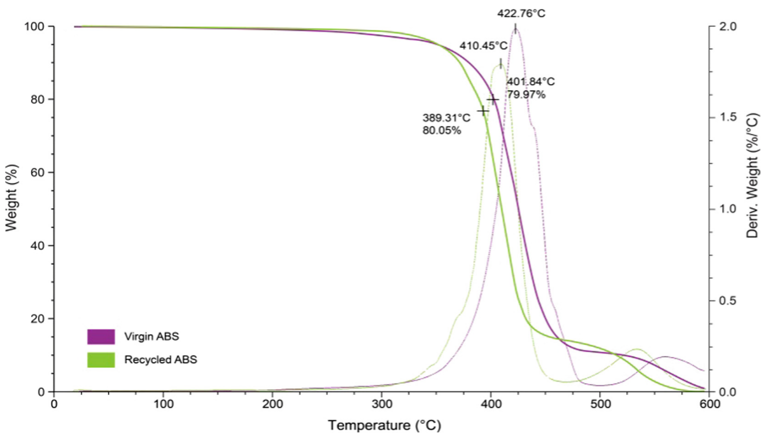



**Fig. 3.** Comparative TGA curve of virgin and recycled ABS samples.

Table 4 shows the thermal decomposition stages of the tested material. When compared to the virgin ABS sample, the recycled material showed a higher decomposition onset temperature, whereas the temperature range to decompose was lower. In other words, the degradation of recycled materials takes longer to start, however it occurs more rapidly. Therefore, it should be observed that this difference exists mainly because virgin ABS has an intrinsically more stable chemical composition, since it is a first cycle material.

**Table 4.** Identification of decomposition temperatures of virgin and recycled ABS.

| Samples | 1st Stage | | 2nd Stage | | Degradation temperature (°C) |
|---|---|---|---|---|---|
| | T*i*-T*f* (°C) | Mass loss (%) | T*i*-T*f* (°C) | Mass loss (%) | |
| Virgin ABS | 212–480 | 88.8 | 480–600 | 10.3 | 422.76 |
| Recycled ABS | 240–460 | 85.4 | 460–600 | 14.6 | 410.45 |

### 3.3 Differential Scanning Calorimetry

The DSC results showed an endothermic peak only for the virgin ABS samples, and an exothermic peak followed by an endothermic peak for the recycled ABS sample (Fig. 4). The endothermic peaks represent the movement of molecules at the time of material decomposition. The exothermic peak present in recycled ABS can be attributed to the presence of PC and additives during the recycling process.

Based on the data from all characterization tests, it can be said that recycled ABS begins its degradation at slightly higher temperatures, but in a shorter interval. In processing terms, this may indicate a higher sensitivity to 3D printing temperature. Thus, the data obtained justifies the selected printing temperatures of 205 °C for virgin material and 215 °C for recycled material.

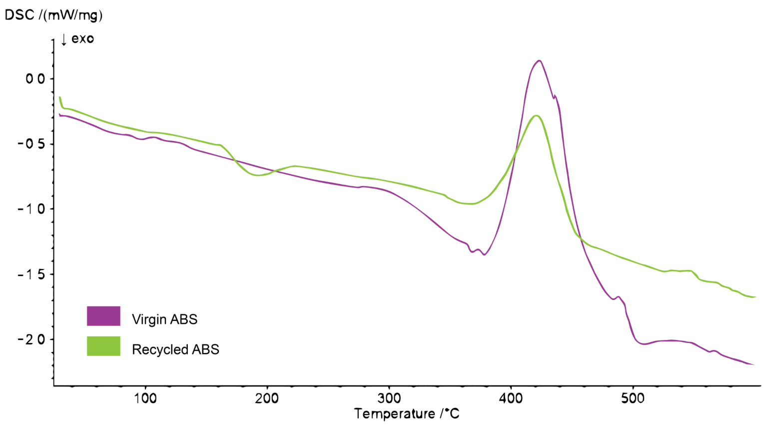



**Fig. 4.** Comparative DSC curve of virgin and recycled ABS.

### 3.4 Tensile Test

During the mechanical tensile tests, the results extracted were: tensile stress, displacement, elongation and elastic modulus (Table 5). Figure 5 shows the samples after tensile test. It is worth mentioning that all the specimens broke, except in the fourth test for recycled ABS, which was caused by a detachment of the outer walls. This event can be

**Table 5.** Results of the tensile test.

| Parameters | Virgin ABS | | Recycled ABS | |
|---|---|---|---|---|
| | Average | Standard deviation | Average | Standard deviation |
| Tensile stress ($N/mm^2$) | 42.68 | 1.0 | 47.84 | 1.2 |
| Displacement (mm) | 1.77 | 0.03 | 1.87 | 0.14 |
| Elongation (%) | 2.91 | 0.06 | 3.06 | 0.22 |
| Elastic modulus ($N/mm^2$) | 2142.50 | 341.48 | 1917.29 | 450.32 |

observed on a smaller scale during other tests and reveals a possible adhesion problem between layers.

This data usually vary a lot between the specimens. In the virgin ABS specimens the results range were: 41,54–43,85 $N/mm^2$ for tensile stress; 1,82–1,74 mm for displacement; 2,85–2,99% for elongation; 1572,36 to 2484,74 $N/mm^2$ for elastic modulus. In the recycled ABS specimens, the results range were: 46,23–48,98 $N/mm^2$ for tensile stress; 1,72–2,00 mm for displacement; 2,82–3,28% for elongation; 1458,84–2592,23 $N/mm^2$ for elastic modulus. That is, the recycled ABS showed a greater variation between values from specimens tested compared to virgin ABS.

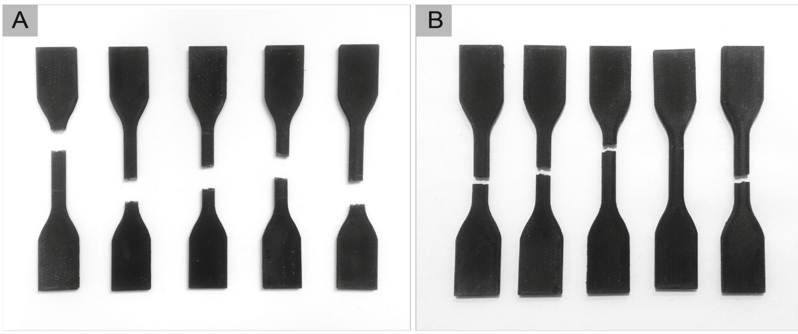



**Fig. 5.** Broken specimens after tensile testing: (a) virgin ABS and (b) recycled ABS.

Quantitatively, the results were homogeneous. The samples showed quite similar mechanical properties, however, recycled ABS exhibited slightly higher tensile strength compared to virgin ABS. Figure 6 graphically represents the stress–strain curves of the average of all five samples of both materials.

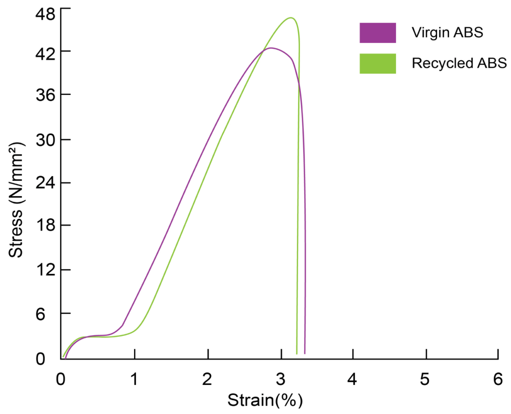



**Fig. 6.** Material stress–strain curves.

## 3.5 Impact Test

In the impact test, the samples did not break completely in the first collision, when hanging only by one of the outer walls. This occurred as a result of the detachment of the contour layers, which allowed the outer wall to bend to the passage of the pendulum hammer and be ruptured upon return. However, when the surfaces were analyzed, the specimens presented a fracture without visible plastic deformations (Fig. 7).

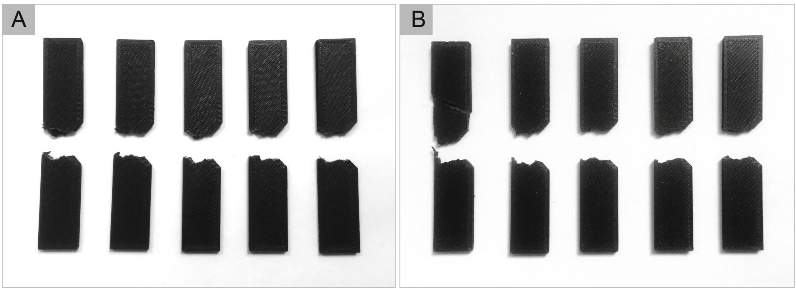



**Fig. 7.** Broken specimens after impact testing: (a) virgin ABS and (b) recycled ABS.

Regarding the results, it can be concluded that the recycled ABS samples absorbed less energy compared to the others, which reveals lower impact strength of this material, as demonstrated in Table 6.

**Table 6.** Results of the Izod impact test.

| Parameters | Virgin ABS | | Recycled ABS | |
|---|---|---|---|---|
| | Average | Standard deviation | Average | Standard deviation |
| Energy absorbed (%) | 5.65 | 0.44 | 2.39 | 0.23 |
| Impact strength (kJ/m$^2$) | 7.97 | 0.62 | 3.29 | 0.32 |
| Impact energy (J) | 0.31 | 0.02 | 0.13 | 0.01 |

## 4 Conclusions

This study contributed to the characterization of commercially available virgin and recycled ABS filaments to provide with useful additional information on the mechanical properties of 3D printed specimens. Contrary to most research on recycled filaments, which comes from artisanal recycling processes, the commercial filaments analyzed in this study were serially manufactured. That is to say, raw materials go through more controlled processes to reduce performance variability.

The results showed some differences between the two materials, both in characterization and mechanical performance tests. The most significant difference was that virgin ABS proved to be much more resistant to impact. This became evident when it absorbed more than twice energy as it did before rupture. Comparatively, the impact strength of recycled ABS was only 42% of that of virgin ABS. The elastic modulus was 11% lower. In addition, after the preparation of the specimens through 3D printing, it is plausible to say that recycled ABS displayed a little more sensitive behavior to temperature and humidity when compared to virgin ABS. It should be pointed out that this behavior was also observed in experiments with filaments of other recycled materials, as in the case of PLA studied by Anderson (2017).

Loss of mechanical properties can be managed in prototyping, which does not prevent the use of recycled ABS in most cases. Further, the use of recycled filaments can help reduce the environmental impact caused by 3D printed parts and supports sustainable manufacturing. It is concluded, therefore, that filaments produced for FFF 3D printing using commercial recycled ABS can be used by so-called domestic equipment, or even, with due precautions, held to a professional standard.

## References

Anderson, I.: Mechanical properties of specimens 3D printed with virgin and recycled polylactic acid. 3D Print. Addit. Manuf. **4**(2), 110–115 (2017)

Arivazhagan, A., Masood, S. H.: Dynamic mechanical properties of ABS material processed by fused deposition modelling. Int. J. Eng. Res. Appl. (IJERA) **2**(3), 2009–2014 (2012)

Balart, R., Lopez, J., García, D., Salvador, D.: Recycling of ABS and PC from electrical and electronic waste. Effect of miscibility and previous degradation on final performance of industrial blends. Eur. Polym. J. **41**, 2150–2160 (2005)

Berman, B.: 3 - D printing: the new industrial revolution. Bus. Horiz. **55**(2), 155–162 (2012)

Denari, G.B., Cavalheiro, E.T.G.: Princípios e aplicações de análise térmica, Instituto de Química de São Carlos, Universidade de São Paulo. São Carlos, available at: http://www.teses.usp.br/teses/disponiveis/75/75135/tde-04042013151955/publico/GabrielaBuenoDenari_Revisado_Anexo.pdf (accessed june 2019) (2012)
Divyathej, M.V., Varun, M., Rajeev, P.: Analysis of mechanical behavior of 3D printed ABS parts by experiments. Int. J. Sci. Eng. Res. **7**(3), 116–124 (2016)
Dizon, J.R.C., Espera, A.H., Jr., Chen, Q., Advincula, R.C.: Mechanical characterization of 3D-printed polymers. Addit. Manuf. **20**, 44–67 (2018)
Dul, S., Fambri, L., Pegoretti, A.: Fused deposition modelling with ABS–graphene nanocomposites. Compos. A Appl. Sci. Manuf. **85**, 181–191 (2016)
Fayazbakhsh, K., Movahedi, M., Kalman, J.: The impact of defects on tensile properties of 3D printed parts manufactured by fused filament fabrication. Mater. Today Commun. **18**, 140–148 (2019)
Ferreira, A.C., Diniz, M.F., Mattos, E.D.C.: FT-IR methodology (transmission and UATR) to quantify automotive systems, Polímeros (AHEAD), 0–0 (2018)
Goh, G.D., Agarwala, S., Goh, G.L., Dikshit, V., Sing, S.L., Yeong, W.Y.: Additive manufacturing in unmanned aerial vehicles (UAVs): challenges and potential. Aerosp. Sci. Technol. **63**, 140–151 (2017)
Gomez-Gras, G., Jerez-Mesa, R., Travieso-Rodriguez, J.A., Lluma-Fuentes, J.: Fatigue performance of fused filament fabrication PLA specimens. Mater. Des. **140**, 278–285 (2018)
Griffiths, A., Howarth, J., De Almeida-Rowbotham, G., Rees, A., Kerton, R.: A design of experiments approach for the optimisation of energy and waste during the production of parts manufactured by 3D printing. J. Clean. Prod. **139**, 74–85 (2016)
Jerez-Mesa, R., Travieso-Rodriguez, J.A., Corbella, X., Busqué, R., Gomez-Gras, G.: Finite element analysis of the thermal behavior of a RepRap 3D printer liquefier. Mechatronics **36**, 119–126 (2016)
Khaki, S., Duffy, E., Smeaton, A.F., Morrin, A.: Monitoring of particulate matter emissions from 3D printing activity in the home setting. Sensors **21**(9) (2021)
Kim, H., Lin, Y., Tseng, T.L.B.: A review on quality control in additive manufacturing. Rapid Prototyp. J. **24**(3), 645–669 (2018)
Lanzotti, A., Martorelli, M., Maietta, S., Gerbino, S., Penta, F., Gloria, A.: A comparison between mechanical properties of specimens 3D printed with virgin and recycled PLA. Procedia CIRP **79**, 143–146 (2019)
Li, J., Chen, F., Yang, L., Jiang, L., Dan, Y.: FTIR analysis on aging characteristics of ABS/PC blend under UV-irradiation in air. Spectrochim. Acta Part A Mol. Biomol. Spectrosc. **184**, 361–367 (2017)
Nadagouda, M., Ginn, M., Rastogi, V.: A review of 3D printing techniques for environmental applications. Curr. Opin. Chem. Eng. **28**, 173–178 (2020)
Perez, A.R.T., Roberson, D.A., Wicker, R.B.: Fracture surface analysis of 3D-printed tensile specimens of novel ABS-based materials. J. Fail. Anal. Prev. **14**(3), 343–353 (2014)
Rayna, T., Striukova, L.: From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. Technol. Forecast. Soc. Chang. **102**, 214–224 (2016)
Roberson, D.A., Perez, A.R.T., Shemelya, C.M., Rivera, A., MacDonald, E., Wicker, R.B.: Comparison of stress concentrator fabrication for 3D printed polymeric izod impact test specimens. Addit. Manuf. **7**, 1–11 (2015)
Rubio, F.V., Silva, J.P., Kaufmann, K.C., Ferreira, M.M., Gonçalves, O.H.: Caracterização de Materiais Poliméricos através da Técnica de FTIR na Região do Infravermelho Médio. In: VII Congresso Científico da Região Centro-Ocidental do Paraná (CONCCEPAR), Centro Universitário Integrado de Campo Mourão, Paraná, available at: https://conccepar.grupointegrado.br/resumo/caracterizacao-de-materiais-polimericos-

atrave-da-tecnica-de-ftir-na-regiao-do-infravermelho-medio/480/759 (accessed January 2020) (2016)

Soares, J.B., Finamor, J., Silva, F.P., Roldo, L., Cândido, L.H.: Analysis of the influence of polylactic acid (PLA) colour on FDM 3D printing temperature and part finishing. Rapid Prototyp. J. **24**(8), 1305–1316 (2018)

Zander, N.E., Gillan, M., Burckhard, Z., Gardea, F.: Recycled polypropylene blends as novel 3D printing materials. Addit. Manuf. **25**, 122–130 (2019)

Yang, S., Castilleja, J.R., Barrera, E.V., Lozano, K.: Thermal analysis of an acrylonitrile–butadiene–styrene/SWNT composite. Polym. Degrad. Stab. **83**(3), 383–388 (2004)

# Material Selection for Ornamental Products Based on Carbon Footprint and Embodied Water

Devanshu Mudgal, Emanuele Pagone(✉), and Konstantinos Salonitis

School of Aerospace, Transport, and Manufacturing (SATM), Cranfield University, Bedford MK43 0AL, UK
e.pagone@cranfield.ac.uk

**Abstract.** This paper analyses and compares the Life Cycle Assessment of ceramics, bricks, steel, clay, and polypropylene with cast stone widely used in architectural ornaments. Architectural ornaments include, for example, statues, Georgian architectural window surrounds and balustrading etc. A methodology was proposed within this study which was verified after being applied to the case study. The Life Cycle Assessment of all the materials was performed from "cradle-to-gate" for a kilogram of each material. The transportation of the finished goods is also included in this study as that is a crucial part of a business. The selected materials were compared based on the overall carbon dioxide equivalent, water, and energy consumption during the general manufacturing process. Materials were plotted at the end of this study based on each parameter. Concrete showed the lowest contribution towards the carbon dioxide equivalent whereas cast stone had the lowest water consumption. Polypropylene had the highest energy consumption. A few recommendations to make cast stone greener were also made at the end of this paper.

**Keywords:** Cast stone · Life cycle analysis · Carbon footprint · Embodied water

## 1 Introduction

Life Cycle Assessment (LCA) has gained popularity among researchers and companies to estimate the environmental performance of construction materials widely used [1]. The focus of the current LCA studies has mainly been on the energy efficiency of the building and its Green House Gas (GHG) emission during its life cycle [2]. As per Persson et al., in the majority of the European countries, the primary energy consumption by the buildings is 40% of the total energy consumption [3]. However, some recent studies have been used to improve the designs of the buildings [4, 5] and compare different construction materials [2]. Although the operational phase of such a building contributes around 90% of its total life cycle energy use but the construction phase is also responsible for contributing a significant amount of energy consumption [6, 7]. Such a comparison could help in finding a more energy-efficient alternative.


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 213–222, 2023.
https://doi.org/10.1007/978-981-19-9205-6_20

There are several studies done to perform LCA of various building materials where concrete was included. One such study was performed by Bribián et al. where the total embodied energy of 1 kg of commonly used raw materials were analysed. The study measured the energy consumption during the building construction stage with commonly used raw materials and eco-materials [8]. The raw materials in the study include ordinary, light clay and sand-lime brick. It also included ceramic and quarry tiles along with ceramic roof tiles and concrete roof tiles and insulation material. The study assessed Water Demand (WD), Global Warming Potential (GWP) and Primary Energy Demand (PED). Among the tiles, the ceramic tile had 15 MJ-Eq/kg of PED, 14.453 L/kg of WD and 0.857 kg $CO_2$-Eq/kg of GWP making it the highest. Concrete tiles are a greener alternative to ceramic tiles with PED 2.659 MJ-Eq/kg, WD of 0.270 kg $CO_2$-Eq/kg GWP and WD of 4.104 L/kg. Among the ordinary and sand-lime bricks, the light clay brick had the lowest GWP at -0.004 kg $CO_2$-Eq/kg but had 1.41 l/kg of water consumption and 6.25 MJ-Eq/kg of PED.

Similarly, a study done by the Souza et al., where ceramic brick, concrete brick, and cast-in-place reinforced concrete for exterior walls were analysed [2]. Cement is an active ingredient of concrete and cement requires 20% more energy than ceramic bricks. The reason being, for concrete, high temperatures reaching 1450 °C is required which is achieved using fossil fuels. Whereas, for ceramic bricks, a temperature of 950 °C is required which is achieved by burning residual wood chips making ceramic bricks greener than concrete. The study also covered steel production as cast-in-place concrete requires steel reinforcement, making cast-in-place concrete less green than ceramic brick walls. To reduce the environmental impact, two recommendations were given by the author. Firstly, the use of a fine particle filtration system for wood chip burner and secondly, the use of biofuels during the shipment of the fuels.

In another study performed by Lasvaux [9] where 28 different materials commonly used in construction were used to perform LCA. The aim of the study was to check if the LCA databases used in the studies display the expected result when compared to the generic databases as it depends on the background impact data. To perform this study, the study assessed numerical and methodological differences between two existing LCA databases for the LCAs i.e., ecoinvent and a French database called Environmental Product Declaration (EPD) database. It was found in the study that a considerable amount of deviation was seen due to assumptions taken in the databases.

Numerous LCA studies have been done to compare the roofing on the buildings [10, 11]. In the study performed by Bianchini et al., roofs made from the greener alternatives such as low-density polyethene and polypropylene polymer are compared. Similarly, Kosareo et al., performed a comparative ‘cradle-to-gate’ LCA of three types of roofing systems i.e., conventional, extensive green, and intensive green. One study performed by Amaral et al., have performed brief LCA on the naturally quarried ornamental stone such as Marble and Granite [12].

Cast stone is a manufactured stone whose mixed composition is designed to replicate the natural stone [13]. It is widely used as an ornamental stone since the 1770s [14]. Recently, the demand of cast stone has also increased [13]. As it is part of the construction sector none of the studies have mentioned cast stone in their studies.

However, none of the studies mentioned above has performed comparative LCA on the ornamental cast stone. The aim of this study is to compare ornamental cast stones to other construction materials used as ornaments for carbon emissions and embodied water. Cast stone would be compared against steel [15], ceramic [16], concrete [17], polypropylene, cast iron, steel, and clay [12] as they are used widely in making architectural ornaments. The system boundary will be from "cradle-to-gate", but the transportation is also considered as it also a crucial aspect of a business.

LCA could get affected by the data gathered from several uncertain secondary sources [18]. As per Cellura et al., the uncertainty could be due to the methodology used, initial assumptions and the system boundaries and the quality of the data collection. In this study a sensitivity analysis is also performed in the results section.

## 2 Methodology

LCA can be performed in various ways as per the requirements of the organization as per ISO 14040:2006 [19]. The methodology used in this paper was divided into different steps presented below. The steps used in this methodology are shown in the Fig. 1.

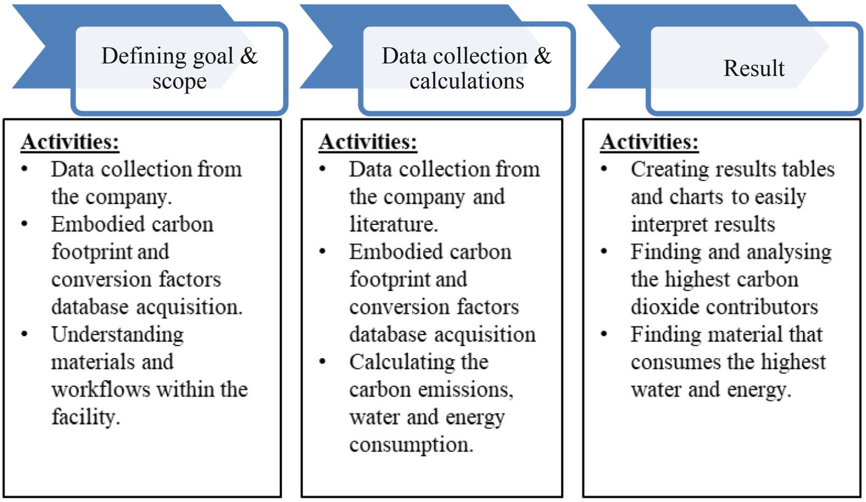



**Fig. 1.** Methodology

### 2.1 Defining Goal and Scope

The goal of this study is to compare carbon dioxide emissions and embodied water of different materials used in producing architectural ornaments. The system boundaries for this study are from 'cradle-to-gate' i.e., from the point of getting raw material till the final product has been shipped to the customer. To have a valid comparison between different materials, a functional unit is chosen as each material has different density and properties. In this study 1 kg is used as a functional unit.

## 2.2 Data Collection and Calculations

For data collection, various databases can be used such as Ecoinvent [20], and Environmental footprints [21] the missing information can also be added to these data bases through the literature review. Data can also be collected from the factory to make the study more accurate. In this step, assumptions are taken (if needed) before calculating the carbon footprint and embodied water. Embodied carbon and water in the raw material is calculated in this step as well. As the study is 'cradle-to-gate', the transportation of the product to the customer is also considered within the boundaries of this system.

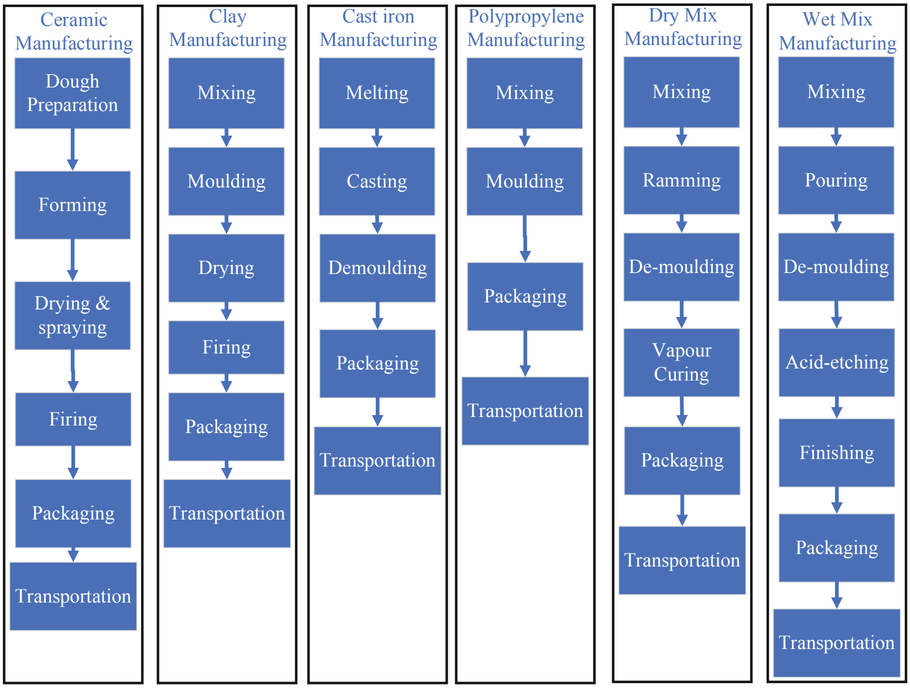



**Fig. 2.** Manufacturing process of different materials and the system boundary

## 2.3 Result and Analysis

After calculating the carbon footprint, in this step, the results are plotted and analysed. For better comparison and interpretation between different materials, the results can be broken down into different sections. Each section will represent separate indicator. For instance, one section would represent carbon footprint and another section embodied water.

# 3 Case Study

## 3.1 Defining Goal and Scope

The above-mentioned methodology was applied to a cast stone manufacturing company based in the UK. The study aims to perform comparative LCA on cast stone with clay, ceramic, cast iron, polypropylene, steel, and concrete based on the $CO_2$ produced per kilogram as well as water consumed and energy demand of the materials. There are 3 types of cast stone i.e., Dry mix, Teclite and Tecstone. The system boundaries for all the materials in this case study are shown in Fig. 2.

In ceramic manufacturing traditionally, a dough is prepared using mechanical mixer. In this step the extracted clay is mixed with other compounds. This step is followed by the mechanical shaping process where mechanical shaping of the ceramic is done. The shape of the ceramic depends on the moulds used. During the drying phase the water content is reduced from 25% to 3% and the ceramic becomes solid. It is also sprayed with a glossy layer that stick to the surface after the firing process. In the firing process, a furnace is used to bake the ceramic with a temperature up to 950 °C. Once baked properly the product is packed and shipped [4].

Clay manufacturing follows a similar to ceramics, where a mixture of clay with other additives are moulded into the desired shape. Once it has taken the shape it is baked in a kiln where it becomes solid. Once the final product is made, it is packed and shipped [22].

Casting process of iron requires melting of iron which is then casted into the desired shape using a mould. Once iron is at the room temperature, mould is opened, and the casted iron goes through a finishing process where any extra metal is removed, or the product is polished. After polishing the product is packed and shipped to the customer.

Polypropylene is an olefin obtained from the fossil fuel [23]. Usually, the granular polypropylene is used for injection moulding process where the granules are melted and injected into a mould where it takes the desired shape. Once it is at the room temperature, the product is packed and shipped.

Cast stone are of three types i.e., Wet mix, Teclite and Dry mix. Teclite and Wet mix follow similar process, where a mix of sand, cement and admixtures are mixed in a calculated proportion. During the mixing stage in Teclite glass fibre is added to the mix whereas, in Wet mix, aggregates are added to the mix. The finished mix is poured into a mould of the desired shape which is demoulded the next day after it is cured. The cast stone is then taken for an acid etching process where Hydrochloric acid (HCl) is used to remove any oil and top surface which exposes aggregates. Once acid etched, the final product is taken for finishing where any imperfections are dealt with as desired shapes made from cast stone can be complex. Once finishing completes the final product is taken for packaging and then it is shipped to the customer. Whereas in Dry mix the no aggregates or glass fibre is added to the mix. As the name suggests Dry mix is a dry powder like substance that is rammed into the mould. Once it is rammed into the mould it is left overnight for curing and then it is de-moulded the next day. After it is de-moulded, it is taken for the vapour curing process where steam is used to fasten the process of curing. This increases the strength of the cast stone. Once cured, it is taken for packaging and then it ready to be transported to the customer. Concrete follows similar procedure where a mix is created which is casted into the desired shape [13].

### 3.2 Data Collection and Calculations

A model of manufacturing process for all the raw materials was created in SimaPro 9 and the ecoinvent data base was used. Ecoinvent database comes with two classifications and three system models. For this case study, market transformation classification was chosen for the material comparison as it considers the transportation of the of raw materials hence the emissions from transportation are included. Also, 'cut-off by classification' system method was used for ease in analysing the default system model. Simapro 9 follows an International Standard ISO 14044:2006 of process-based model with the LCA assessment to be defined in 4 key phases such as 'Define goal and scope', 'Life cycle inventory analysis' (LCI), and 'Impact Assessment' and 'Interpretation'. In the Life Cycle Inventory (LCI), product stage subcategory was selected as it allows the analysis to be performed in a 'cradle-to-gate' boundary. The indicators used were carbon dioxide and climate change biogenic. Company provided any missing data which was entered into the ecoinvent database.

As the concrete's mix design varies for each purpose, it was assumed for this study that no admixtures were added to the concrete block. The composition for concrete and steel was taken from Bribian et al. which were used in SimPro 9 [8]. For this study, the concrete selected is a low strength general purpose concrete. Also, the steel composition selected during the study is chromium steel 18/8 from the ecoinvent database. The method used for carbon dioxide and the water consumption is ReCiPe 2016 v1.1 midpoint whereas to calculate the energy consumption, Cumulative Energy Demand (CED) is used.

### 3.3 Results and Analysis

After performing the calculation in SimaPro 9, the results were obtained. Overall, it was found that the biggest Carbon dioxide emitter was steel at 6.44 kg $CO_2$-Eq /kg and the lowest being concrete block at 0.158 kg$CO_2$eq/kg as shown in Table 1. The second biggest contributor of carbon dioxide was the Polypropylene (3.68 kg$CO_2$eq/kg) which is a thermoplastic polymer obtained from fossil fuel which justifies the high emissions. Among all the cast stones, the Wet mix was the lowest carbon emitter with 0.478 kg$CO_2$eq/kg followed by the Dry mix at 0.594 $CO_2$ Eq /kg.

Similarly, for the water usage Wet mix uses the lowest amount of water per kg. It uses 0.000029 $m^3$/kg, whereas polypropylene has the highest water use i.e., 0.0355 $m^3$/kg. Steel has the second highest water consumption of 0.0355 $m^3$/kg. Such low water consumption in cast stone is due to the use of super plasticizer. In terms of Energy consumption, polypropylene ranks the highest with 97.2 MJ for per kg and the concrete block ranks the lowest 1.28 MJ/kg. Carbon dioxide, water consumption and energy demand are plotted in Figs. 3, 4 and 5 respectively for easy comparison for the decision-makers.

However, for this study the density of each material is not taken into consideration so, for instance, if a specific part is produced the density of each material will vary which also would affect the weight of the part.

**Table 1.** Carbon dioxide, water consumption and energy demand of different materials

| Building material | Carbon dioxide (kg $CO_2$-Eq /kg) | Water consumption ($m^3$/kg) | Energy demand (MJ/kg) |
|---|---|---|---|
| Dry Mix (DM) | 0.616 | 0.000094 | 4.344 |
| Teclite Mix (TM) | 0.824 | 0.000071 | 5.47 |
| Wet Mix (WM) | 0.478 | 0.000029 | 3.228 |
| Cast Iron (CI) | 1.93 | 0.00972 | 17.5 |
| Ceramics (Cs) | 0.825 | 0.00674 | 11 |
| Clay (C) | 3.49 | 0.0157 | 54.7 |
| Concrete Block (CB) | 0.158 | 0.00135 | 1.28 |
| Polypropylene (P) | 3.68 | 0.0355 | 97.2 |
| Steel (S) | 6.44 | 0.0276 | 74.2 |

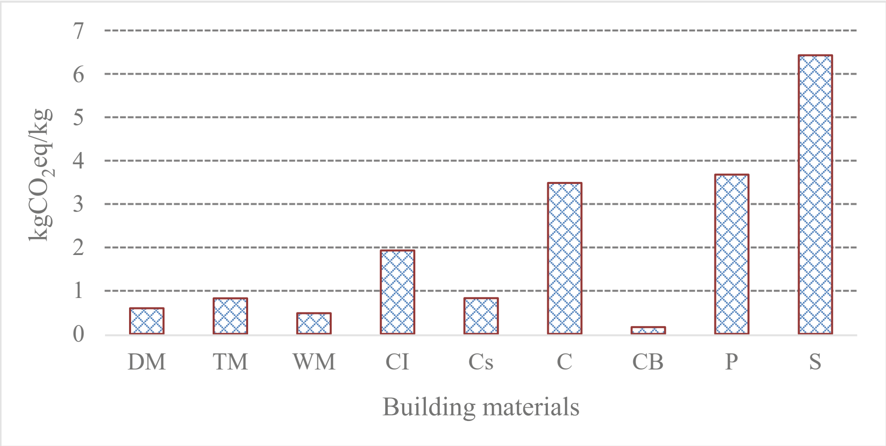



**Fig. 3.** Carbon dioxide emissions where DM- Dry Mix, TM- Teclite Mix, WM-Wet Mix, CI-Cast Iron, Cs- Ceramics, C- Clay, CB-Concrete Block, P- Polypropylene and S-Steel

To deal with uncertainty, a sensitivity analysis was performed. The input weight of each criterion was changed. The weight was increased 5%, 10%. 15% and 20% of 1 kg of each material in SimaPro model. The error was plotted in Fig. 6, where error in Steel is 0.22 and lowest was concrete block with an error of 0.005.

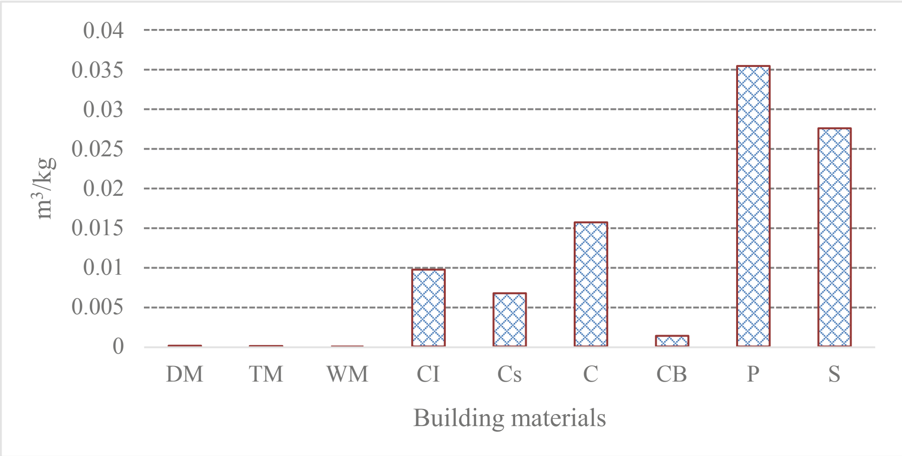



**Fig. 4.** Water consumption where DM- Dry Mix, TM- Teclite Mix, WM-Wet Mix, CI-Cast Iron, Cs- Ceramics, C- Clay, CB-Concrete Block, P- Polypropylene and S-Steel

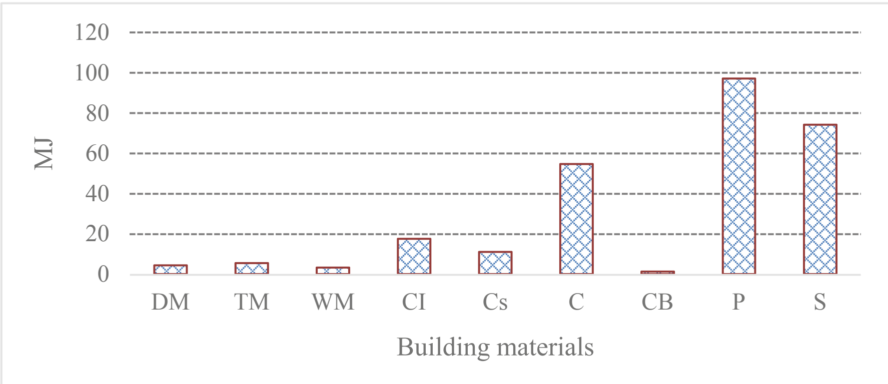



**Fig. 5.** Energy demand where DM- Dry Mix, TM- Teclite Mix, WM-Wet Mix, CI-Cast Iron, Cs- Ceramics, C- Clay, CB-Concrete Block, P- Polypropylene and S-Steel

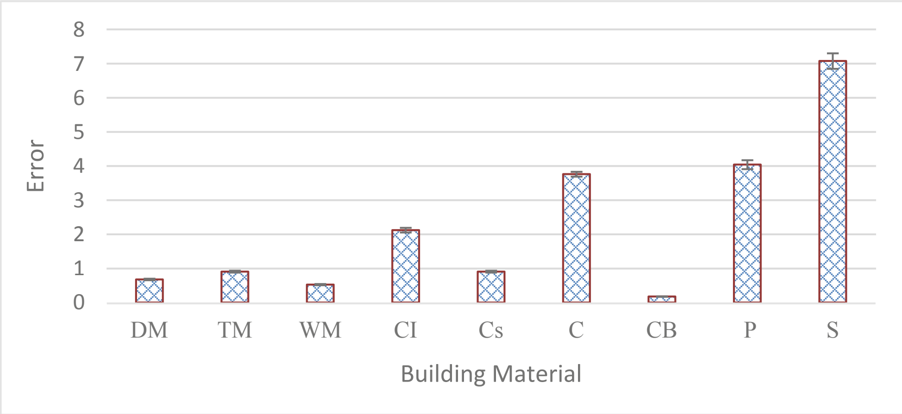



**Fig. 6.** Error bar chart $CO_2$-Eq, where DM- Dry Mix, TM- Teclite Mix, WM-Wet Mix, CI-Cast Iron, Cs- Ceramics, C- Clay, CB-Concrete Block, P- Polypropylene and S-Steel

## 4 Conclusion

This study aimed to compare LCA of various materials widely used in architectural ornaments. A methodology was proposed in this study which was verified by applying to the case study. From the caste study, it could be concluded that proposed methodology worked for comparing cast stone with different material. From the results, concrete block had the lowest carbon dioxide emissions in among all the raw material followed by Wet mix cast stone. Polypropylene had the highest carbon dioxide emission. Among the cast stone, Teclite had the highest carbon dioxide emissions. However, more improvement can be made to reduce the carbon footprint for cast stone by finding alternatives to the packaging and cement within the raw material of the cast stone's mix. As manufacturing of cement is an energy intensive process. As part of the future work, more parameters can potentially be included into the study which allow better decision making and material selection and for uncertainty analysis.

## References

1. Buyle, M., et al.: Life cycle assessment in the construction sector: a review. Renew. Sustain. Energy Rev. **26**, 379–388 (2013)
2. De Souza, D.M., et al.: Comparative life cycle assessment of ceramic brick, concrete brick and cast-in-place reinforced concrete exterior walls. J. Clean. Prod. **137**, 70–82 (2016)
3. Persson, J., Grönkvist, S.: Drivers for and barriers to low-energy buildings in Sweden. J. Clean. Prod. **109**, 296–304 (2015)
4. de Souza, D.M., et al.: Comparative Life Cycle Assessment of ceramic versus concrete roof tiles in the Brazilian context. J. Clean. Prod. **89**, 165–173 (2015)
5. Saiz, S., et al.: Comparative life cycle assessment of standard and green roofs. Environ. Sci. & Technol. **40**(13), 4312–4316 (2006)
6. Dimoudi, A., Tompa, C.J.R.: Energy and environmental indicators related to construction of office buildings. Conserv. Recycl. **53**(1–2), 86–95 (2008)

7. Pérez-Lombard, L., et al.: A review on buildings energy consumption information. Energy Build. **40**(3), 394–398 (2008)
8. Bribián, I.Z., et al.: Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. **46**(5), 1133–1140 (2011)
9. Lasvaux, S., et al.: Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. Int. J. Life Cycle Assess. **20**(11), 1473–1490 (2015)
10. Kosareo, L., Ries, R.J.B.:Comparative environmental life cycle assessment of green roofs. Build. Environ. **42**(7), 2606–2613 (2007)
11. Bianchini, F., Hewage, K.J.B.: How "green" are the green roofs? Lifecycle analysis of green roof materials. Build. Environ. **48**, 57–65 (2012)
12. Amaral, P.M., et al.: Ornamental stones, in Materials for Construction and Civil Engineering, pp. 397–445. Springer (2015)
13. Mudgal, D., et al.: Life-cycle-assessment of cast stone manufacturing: a case study. Procedia CIRP **104**, 624–629 (2021)
14. Association, U.C.S. About cast stone. Coade Stone [cited 2022 30/04/2022]; Available from: https://ukcsa.co.uk/history-of-cast-stone/
15. Marquès, J.A., Arias, J.S.: Metalurgia medieval aplicada a la construcción. Las rejas góticas de la Catedral de Barcelona. Arqueología de la Arquitectura **12**, 8 (2015)
16. Kim, S.-M.: The study design of ceramic ornaments. J. Digit. Converg. **11**(2), 391–396 (2013)
17. Hunter, S.W.: Creative Concrete Ornaments for the Garden: Making Pots, Planters, Birdbaths, Sculpture & More. Sterling Publishing Company, Inc. (2005)
18. Cellura, M., et al.: Sensitivity analysis to quantify uncertainty in life cycle assessment: the case study of an Italian tile. Renew. Sustain. Energy Rev. **15**(9), 4697–4705 (2011)
19. assessment–Principles, I.S.O.J.E.m.L.c. and framework, ISO 14040: 2006. 2006
20. Ecoinvent. Database. [cited 2022 03/05/2022]; Available from: https://ecoinvent.org/the-ecoinvent-database/
21. Comission, E. European Platform on Life Cycle Assessment. [cited 2022 03/05/2022]; Environmental footprints]
22. Bories, C., et al.: Development of porous fired clay bricks with bio-based additives: Study of the environmental impacts by Life Cycle Assessment (LCA). Constr. Build. Mater. **125**, 1142–1151 (2016)
23. Diercks, R., et al.: Raw material changes in the chemical industry. Chem. Eng. & Technol.: Ind. Chemistry-Plant Equipment-Process Engineering-Biotechnology **31**(5), 631–637 (2008)

# Comparative Study of Multi-criteria Decision Analysis Methods in Environmental Sustainability

Emanuele Pagone(✉) and Konstantinos Salonitis

Sustainable Manufacturing Systems Centre, School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield MK43 0AL, UK
e.pagone@cranfield.ac.uk

**Abstract.** Multi-Criteria Decision Analysis (MCDA) is an operations research framework used to support decision-makers in choosing alternatives characterized by multiple conflicting criteria. Over the past years, several MCDA methods have been developed and a significant drawback of using more than one algorithm for a given problem is the potential conflicting ranking that they may yield. This work aims at setting the first steps toward a systematic framework that reconciles different rankings from MCDA methods and returns to the decision maker a unique solution. The proposed method is contextualised within the existing scientific literature and illustrated considering four case studies to select environmentally sustainable solutions. Results show that a ranking agreed by multiple MCDA methods is more reliable than a ranking obtained by one method.

**Keywords:** Multiple-criteria decision making · Sustainable manufacturing · Conflict ranking · Alternative occurrences

## 1 Introduction

Multiple-Criteria Decision Analysis (MCDA) – also known as Multi-Criteria Decision-Making (MCDM) – is an efficient and effective operations research tool to evaluate and solve decision-making problems that involve conflicting criteria providing a final ranking of the considered alternatives "from best to worst". MCDA has seen significant interest over the past years, and it has been applied to a number of different areas, including sustainable design and manufacturing. Several MCDA methods have been proposed, each of them with peculiar strengths and weaknesses. However, although applying more than one MCDA method to a given problem is beneficial (because it can increase the confidence in the final decision making), one significant drawback is that conflicting rankings can be obtained.

This work describes the first steps in developing a structured, systematic framework able to reconcile conflicting rankings from various MCDA methods and return to the decision maker a unique final solution. A comprehensive literature review is performed to gain an understanding of the existing approaches


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 223–231, 2023.
https://doi.org/10.1007/978-981-19-9205-6_21

followed by a critical analysis of relevant advantages and disadvantages. Finally, a first attempt to develop a new reconciliation method is outlined and applied considering five MCDA methods: TOPSIS, VIKOR, ELECTRE, MULTIMOORA and WASPAS. Input data from four case studies related to environmental sustainability choices are collected and applied to the five MCDA methods. Finally, the proposed ranking reconciliation method is applied to illustrate its use and validate its effectiveness.

## 2 Conflicting MCDA Ranking Reconciliation Approaches

A notable limitation of applying multiple MCDA methods is that they may return dissimilar results (i.e. rankings) for the same problem, and it is often not simple to identify one MCDA method as the most suitable for a given decision problem. MCDA techniques have their restrictions, hypotheses, theories and perspectives, which may lead to distinctive outcomes when applied to the same problem. Additionally, the choice of specific MCDA methods can be subjectively related to the decision maker preferences and assumptions, making challenging the analysis, evaluation and comparison of different methods [1]. An overview of existing approaches to reconcile conflicting rankings obtained by different MCDA methods follows.

One possible technique to solve the described problem is using Spearman's correlation coefficient to measure the agreement between rankings. Specifically, if conflicting rankings are detected, Kou *et al.* [2] calculated Spearman's rank correlation coefficient $\rho$, first, between pairs of $k$-th and $i$-th MCDA methods

$$\rho_{ki} = 1 - \frac{6\sum_{j=1}^{n} d_j^2}{n(n^2-1)} \tag{1}$$

where $n$ is the number of alternatives and $d_j$ is the difference in ranking of each $j$-th alternative for the $ki$ pair of MCDA methods considered. Then, a coefficient for each $k$-th MCDA method (of the $q$ in total) is obtained

$$\rho_k = \frac{1}{q-1}\sum_{i=1, i\neq k}^{q} \rho_{ki} \qquad k = 1, 2, \ldots, q \tag{2}$$

and it is used (suitably normalized) as weight to combine MCDA scores to return the final, unique ranking [2].

Alternatively, Kendall's tau-b correlation coefficient can be used in a similar way. For example, Zamani-Sabzi *et al.* [3] developed an approach that contrasts the results of different MCDA methods highlighting their similarities and inconsistencies. The authors selected 10 MCDA techniques (including SAW, TOPSIS, AHP, ELECTRE, VIKOR) and statistically evaluated their conflicting rankings using Kendall's tau-b correlation coefficients $\tau_B$ [3]. In general, for each pair $k$-th and $i$-th of MCDA methods, $\tau_{B,ki}$ is calculated in the following way

$$\tau_{B,ki} = \frac{n_c - n_d}{\sqrt{(n_0 - n_k)(n_0 - n_i)}} \tag{3}$$

where $n_c$ and $n_d$ are the number of concordant and discordant pairs between methods $k$ and $i$. Terms $n_0$, $n_k$ and $n_i$ are calculated as follows

$$n_0 = \frac{n(n-1)}{2} \quad n_k = \sum_j \frac{t_j(t_j-1)}{2} \quad n_i = \sum_l \frac{u_l(u_l-1)}{2} \tag{4}$$

where $n$ is the number of alternatives, whereas $n_k$ and $n_i$ take into account of potential ties in the ranking of the respective $k$-th and $i$-th MCDA method. Specifically, $n_k$ is constructed counting how many groups of ties are present in the ranking and, for each $j$-th group, measures the number of tied alternatives in that group $t_j$. Similarly, $n_i$ is calculated on the basis of the number of tied alternatives $u_l$ for each $l$-th group of ties in the ranking of the $i$-th MCDA method. Then, $\tau_B$ coefficients can be used by the decision maker to appreciate the magnitude of correlation between methods and select the simplest method that produces reasonably similar ranks to the others. Alternatively, it is possible to calculate a weight coefficient for each MCDA method substituting $\tau_{B,k}$ to $\rho_k$ into (2).

Mohammadi and Rezaei propose a method to minimize the distance between each ranking using half quadratic theory to approximate the overall aggregate ranking $R^*$ [4]. The principle behind this method is to assign weights proportional to the difference of rankings and are, therefore, objectively set. Such weights are then used to calculate the final, output ranking [4]. The minimization function is

$$\min_{R^*} \frac{1}{2} \sum_{k=1}^{q} ||R_k - R^*||^2 \tag{5}$$

with $q$ the number of MCDA methods considered and $R_k$ the ranking of the $k$-th MCDA method. The arithmetic mean of the rankings is the closed-form solution of the minimization problem of $R^*$ that has been found [4]:

$$R^* = \frac{1}{q} \sum_{k=1}^{q} R_k \tag{6}$$

More reliability is achieved introducing two indicators: the consensus index and trust level. The consensus index is an indicator that shows the agreements between MCDA methods, while the trust level reports the reliability of the resulting final ranking. If there is an agreement between the methods, the consensus index and trust level are equal to $1/q$ which means that their values are both high. If there is a disagreement between all the ranks, then their values are low [4].

A fourth method that can be considered is the Fusion approach [2]. In this case the weights from different MCDA methods are determined by seeking a compromising ranking that has a minimized solution between the overall rankings and the optimal result [2]. To calculate the relevant weights $w_k$, the rankings of $q$ MCDA methods $R_k$ are combined to obtain the compromise ranking $R^*$

$$R^* = \sum_{k=1}^{q} w_k \, R_k \tag{7}$$

Then, it is selected among the available rankings $R_k$ the one with the minimum difference from the optimal $R^*$ calculated [2].

A fifth method of consideration is using the Gini Index which is one of the primary metrics to measure statistical heterogeneity. Selmi *et al.* [5] propose a comparative study to identify the similarities and differences between MCDA methods to reconcile conflicting rankings. The Gini index $D$ used to measure the ranking dispersion is defined as:

$$D = \frac{4}{(n-1)(q^2 - |\sin\frac{q\pi}{2}|)} \sum_{k=1}^{q-1} \sum_{i=k+1}^{q} |R_k - R_i| \tag{8}$$

where $n$ is for the number of alternatives, $R_k$ and $R_i$ are the position in the ranking according to methods $k$ and $i$, whereas $q$ is the number of MCDA methods. Equation (8) provides a normalised value between zero (same rankings) and one (ranking highly dependent on the MCDA method). $D$ can be calculated for each alternative to assess the stability of the ranking across all the methods considered. However, such values are intended only to support the decision maker that is, then, left to decide a compromised ranking, without a structured procedure to follow [5]. Furthermore, $D$ could be also evaluated between pairs of MCDA methods to appreciate similarities between them for the problem at hand [5].

A final method of consideration is at the basis of the SIMUS software, as proxy method [6]. The creator of SIMUS claims that there is always a risk of disagreement between various MCDA methods caused by their inherent procedural subjectivity linked (for example) to criteria weighting [7]. The proposed solution by SIMUS is based on linear programming that leads to rankings independent from the normalization method and removes subjectivity from the decision making process [7].

Considering pros and cons of the described methods (Table 1), there is no ideal solution to reconcile conflicting MCDA rankings in the literature. Therefore, a new approach is proposed and implemented in this work as a first step towards a complete method able to reconcile multiple, conflicting rankings with minimal shortcomings.

## 3 A Novel Reconciliation Method

An approach based on the mode of the position in the rankings for each alternative is proposed and it is based on the principle that the preferable solution is the one with the widest agreement among the MCDA methods. Furthermore, this approach implies that no MCDA method is better than the others and allows to scale the approach to any desired number of MCDA methods automatically. One restriction to the proposed approach in the current form is that the number of MCDA methods to be considered must be odd to avoid ambiguities in the final ranking obtained.

The approach will be illustrated and tested with four case studies pertaining sustainability and extracted from the scientific literature.

**Table 1.** Advantages and limitations of existing approaches to reconcile conflicting rankings by multiple MCDA methods found in the scientific literature

| Reconciliation method | Pros | Cons |
|---|---|---|
| Spearman's coefficient | No assumption about data distribution | Requires calculation of weights and pairwise comparison for each MCDA method |
| Kendall's coefficient | No assumption about data distribution | Requires calculation of weights and pairwise comparison for each MCDA method |
| Half quadratic theory | Simple calculation (arithmetic mean) | Might be too simplistic and Require rank position rounding |
| Gini index | Provides a bounded measure of dispersion of rankings between 0 and 1 | No structured procedure to obtain the final ranking |
| Fusion approach | Simple formula to apply | Requires calculation of weights for each MCDA methods Two output rankings |
| SIMUS | Totally objective method | |

## 4 Results and Discussion

To illustrate and test the effectiveness of the proposed approach, four case studies in the field of sustainability were collected from the scientific literature. More specifically, for each case study, data comprising the typical decision making matrix were extracted: i.e. alternatives, criteria and their measure of performance along with an indication of their beneficial or non-beneficial impact (i.e. a greater value is better or worse). Rankings were calculated according to five well-established MCDA methods: TOPSIS [8,9], VIKOR [10], MULTIMOORA [11], WASPAS [12], and ELECTRE [13]. The cases were evaluated using the R computer language [14] package MCDM [15].

Case study 1 compares competing plans to build a sewer network. The criteria considered are the dynamic performance in terms of flow volume, the cost of construction to implement the plan, the cost of maintenance for inspection or repairing, the environmental impact and the potential future profit [16]. It can be seen that, in this case, TOPSIS appears to return a significantly different ranking in comparison to the other MCDA methods (Table 2). Consequently, in this case, TOPSIS has minimal influence on the final ranking.

Case study 2 compares ten different designs of support structures for offshore wind turbines. Ten criteria are considered: compliance or maximum displacement of the rotor, dynamic performance, design redundancy, cost of maintenance, cost of installation, environmental impact of the installation, operation and decommissioning, carbon footprint, certification, likely cost of the concept and depth compatibility [17]. In this case there seem to be a lack of agreement between methods with the mode of the position in the ranking showing low

**Table 2.** Case study 1 alternative rankings.

| Alternatives | TOPSIS | VIKOR | MULTIMOORA | WASPAS | ELECTRE | Final ranking |
|---|---|---|---|---|---|---|
| Plan 1 | 4 | 2 | 3 | 2 | 2 | 2 |
| Plan 2 | 1 | 4 | 4 | 4 | 4 | 4 |
| Extension 3 | 3 | 1 | 1 | 1 | 1 | 1 |
| Extension 4 | 2 | 3 | 2 | 3 | 3 | 3 |

frequency (Table 3). In particular, a frequency of two is observed for the alternatives "Jacket" and "Barge".

**Table 3.** Case study 2 alternative rankings.

| Alternatives | TOPSIS | VIKOR | MULTIMOORA | WASPAS | ELECTRE | Final ranking |
|---|---|---|---|---|---|---|
| Jacket | 1 | 9 | 7 | 2 | 2 | 2 |
| Tripod | 2 | 8 | 3 | 3 | 3 | 3 |
| Monopile | 3 | 1 | 1 | 1 | 1 | 1 |
| Suction bucket | 6 | 2 | 5 | 5 | 5 | 5 |
| Jack up | 4 | 7 | 4 | 4 | 4 | 4 |
| Spar | 9 | 6 | 9 | 9 | 10 | 9 |
| Barge | 5 | 4 | 2 | 6 | 6 | 6 |
| TLP | 10 | 10 | 10 | 10 | 9 | 10 |
| Semi-submersible | 7 | 5 | 6 | 7 | 7 | 7 |
| Tri-floater | 8 | 3 | 8 | 8 | 8 | 8 |

Case study 3 compares thirteen renewable energy investment projects considering the following criteria: power, investment ratio, useful life, cost, operating hours, implementation period and the amount of carbon dioxide emissions [18]. It can be observed (Table 4) that there is a good agreement between WASPAS and MULTIMOORA for most of the alternatives, unlike TOPSIS and VIKOR that return dissimilar rankings. Furthermore, this case shows that, when the number of alternatives increases, the agreement between the rankings of MCDA methods usually decreases.

Case study 4 is a material selection investigation to design car bodies with environmentally friendly processes [19]. Ten alternative materials were evaluated in terms of physical properties, durability, suitability to manufacturing processes (called "technical") and environmental properties. In agreement with previous cases, MULTIMOORA and WASPAS return similar rankings influencing with their agreement the final output (Table 5).

As previously briefly mentioned, a factor that appears to cause a significant difference between rankings is the number of alternatives $n$. In case studies 3 and 4 (that are characterized by a relatively large $n$) there is a low frequency of agreed positions in the rankings among MCDA methods. ELECTRE, for

**Table 4.** Case study 3 alternative rankings.

| Alternatives | TOPSIS | VIKOR | MULTIMOORA | WASPAS | ELECTRE | Final ranking |
|---|---|---|---|---|---|---|
| A1 | 13 | 13 | 12 | 13 | 13 | 13 |
| A2 | 11 | 8 | 9 | 10 | 9 | 9 |
| A3 | 2 | 2 | 2 | 2 | 2 | 2 |
| A4 | 12 | 12 | 10 | 11 | 12 | 12 |
| A5 | 10 | 6 | 13 | 12 | 10 | 10 |
| A6 | 4 | 11 | 11 | 9 | 6 | 11 |
| A7 | 3 | 3 | 3 | 3 | 3 | 3 |
| A8 | 9 | 4 | 8 | 8 | 10 | 8 |
| A9 | 7 | 9 | 6 | 6 | 6 | 6 |
| A10 | 7 | 10 | 7 | 7 | 6 | 7 |
| A11 | 6 | 7 | 5 | 5 | 5 | 5 |
| A12 | 1 | 1 | 1 | 1 | 1 | 1 |
| A13 | 5 | 5 | 4 | 4 | 4 | 4 |

**Table 5.** Case study 4 alternative rankings.

| Alternatives | TOPSIS | VIKOR | MULTIMOORA | WASPAS | ELECTRE | Final ranking |
|---|---|---|---|---|---|---|
| Material 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Material 2 | 3 | 2 | 3 | 3 | 2 | 3 |
| Material 3 | 4 | 3 | 5 | 5 | 2 | 5 |
| Material 4 | 6 | 6 | 6 | 6 | 3 | 6 |
| Material 5 | 9 | 10 | 9 | 9 | 9 | 9 |
| Material 6 | 7 | 7 | 8 | 8 | 7 | 7 |
| Material 7 | 8 | 8 | 7 | 7 | 8 | 8 |
| Material 8 | 10 | 9 | 10 | 10 | 6 | 10 |
| Material 9 | 2 | 4 | 2 | 2 | 5 | 2 |
| Material 10 | 5 | 5 | 4 | 4 | 4 | 4 |

example, is particularly sensitive to the value of $n$ because of its estimation of the concordance and discordance matrices [13]. This consideration seems to be reinforced observing that cases with fewer alternatives, like case study 1, show good agreement among methods. However, a broader validation with more cases would be beneficial before drawing a final conclusion.

Since the approach proposed in this work is the result of multiple MCDAs, it provides the decision maker with more confidence in the results, increasing the reliability and robustness of consequent choices. Moreover, another reason that may make a multi-method ranking preferable, is the consideration that, in general, no MCDA method can be considered superior.

On the other hand, an obvious drawback to the adoption of the proposed approach is the additional time required. However, the calculation process of the output ranking has been designed to be quite simple to minimize additional time and effort asked to the decision maker. Another related consideration regards the specific MCDA methods to be included in the set of evaluations. For instance, some methods not presented in this work may require additional work or more resources from the decision makers. For example, the Analytic Hierarchy Process (AHP) requires demanding pairwise comparisons of criteria performed by experts that implies significant additional effort [20]. Furthermore, cases with low consensus among MCDA methods can be still valuable because they signal to the decision maker that any rankings for the specific case at hand do not have a solution that can be trusted.

## 5 Conclusion and Future Work

Different Multiple Criteria Decision Analysis (MCDA) methods are known, in some cases, to return conflicting rankings when applied to the same problem. Since each MCDA method is unique in its way with specific characteristics, the validity of their answers can be questioned by this potential inconsistency. Deep research and analysis of existing approaches to solve this issue were presented in this work and, subsequently, a novel reconciliation approach has been presented. The method is simple and based on the mode of the position in the rankings for each alternative. Four case studies in the field of sustainability were selected and analysed to illustrate and test the applicability of the proposed approach. Based on the results, the new ranking system appears promising and represents an important step into the definition of a framework to reconcile conflicting rankings of multiple MCDA methods.

Areas of further development lie in the handling of special or corner cases (e.g. with methods like AHP or PROMETHEE) and including sensitivity studies to corroborate the robustness of the final ranking. AHP or PROMETHEE introduce different type of thresholds and scaling that may affect the weights and the final ranking of alternatives in a different way compared to the methods considered in this work. Sensitivity can be measured, for example, to test the robustness of the approach against uncertainties in interpretative values or weights. Further validation with more case studies would be also valuable.

**Acknowledgements.** The foundational work carried out by Ms Sahar Hisham Albahkali as part of her MSc thesis project is gratefully acknowledged.

## References

1. Ghaleb, A.M., Kaid, H., Alsamhan, A., Mian, S.H., Hidri, L.: Assessment and comparison of various MCDM approaches in the selection of manufacturing process. Adv. Mater. Sci. Eng. **2020**, 1–16 (2020)
2. Kou, G., Lu, Y., Peng, Y., Shi, Y.: Evaluation of classification algorithms using MCDM and rank correlation. Int. J. Inf. Technol. Decis. Making **11**(1), 197–225 (2012)

3. Zamani-Sabzi, H., King, J.P., Gard, C.C., Abudu, S.: Statistical and analytical comparison of multi-criteria decision-making techniques under fuzzy environment. Oper. Res. Perspect. **3**, 92–117 (2016)
4. Mohammadi, M., Rezaei, J.: Ensemble ranking: aggregation of rankings produced by different multi-criteria decision-making methods. Omega **96**, 102254 (2020)
5. Selmi, M., Kormi, T., Ali, N.B.H.: Comparison of multi-criteria decision methods through a ranking stability index. Int. J. Oper. Res. **27**(1–2), 165–183 (2016)
6. Munier, N., Hontoria, E., Jiménez-Sáez, F.: Analysis of lack of agreement between MCDM methods related to the solution of a problem: proposing a methodology for comparing methods to a reference. In: Strategic Approach in Multi-Criteria Decision Making. ISORMS, vol. 275, pp. 203–219. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-02726-1_11
7. Munier, N.: A new approach to the rank reversal phenomenon in MCDM with the Simus method. Mult. Crit. Decis. Making **11**, 137–152 (2016)
8. Hwang, C.L., Yoon, K.: Multiple Attribute Decision Making: Methods and Applications. Springer-Verlag, New York (1981). https://doi.org/10.1007/978-3-642-48318-9_3
9. Zavadskas, E.K., Mardani, A., Turskis, Z., Jusoh, A., Nor, K.M.: Development of TOPSIS method to solve complicated decision-making problems — an overview on developments from 2000–2015. Int. J. Inf. Technol. Decis. Making **15**(3), 645–682 (2016)
10. Mardani, A., Zavadskas, E.K., Govindan, K., Amat Senin, A., Jusoh, A.: VIKOR technique: a systematic review of the state of the art literature on methodologies and applications. Sustainability **8**(1), 1–38 (2016)
11. Brauers, W.K.M., Zavadskas, E.K.: Project management by MULTIMOORA as an instrument for transition economies. Technol. Econ. Dev. Econ. **16**(1), 5–24 (2010)
12. Zavadskas, E.K., Turskis, Z., Antucheviciene, J., Zakarevicius, A.: Optimization of weighted aggregated sum product assessment. Elektronika ir Elektrotechnika **122**(6), 3–6 (2012)
13. Roy, B.: Classement et choix en présence de points de vue multiples (la méthode ELECTRE). La Revue d'Informatique et de Recherche Opérationelle (RIRO) **8**, 57–75 (1968)
14. R Core Team: R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria (2021)
15. Ceballos Martín, B.A.: CRAN – Package MCDM (2016)
16. Wu, Z., Abdul-Nour, G.: Comparison of multi-criteria group decision-making methods for urban sewer network plan selection. CivilEng **1**(1), 26–48 (2020)
17. Kolios, A., Mytilinou, V., Lozano-Minguez, E., Salonitis, K.: A comparative study of multiple-criteria decision-making methods under stochastic inputs. Energies **9**(7), 566 (2016)
18. San Cristóbal, J.: Multi-criteria decision-making in the selection of a renewable energy project in Spain: the VIKOR method. Renew. Energy **36**(2), 498–502 (2011)
19. Pu, Y., Ma, F., Han, L., Wang, G.: Material selection of green design processes for car body via considering environment property. Math. Probl. Eng. **2020**, 1–8 (2020)
20. Saaty, T.L.: The Analytic Hierarchy Process: Planning, Priority Setting. Resource Allocation. McGraw-Hill International Book Company, London (1980)

# Development of a Database for the Management and Use of Available Resources in the Field of Sustainable Nanomanufacturing

Clarissa Marquardt[1](✉), Steffen G. Scholz[1,2], Katja Nau[1], and Andreas Schmidt[1]

[1] Institute for Automation and Applied Informatics (IAI), Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany
clarissa.marquardt@kit.edu
[2] Karlsruhe Nano Micro Facility (KNMFi), Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany

**Abstract.** The rapid development of nanotechnology-based products and applications over the last three decades has influenced numerous scientific fields and industry sectors ranging from medical applications, food and consumer care up to the semiconductor and the energy sector. The complexity and multidisciplinary needed to approach the topic of sustainability in nanomanufacturing requires a wide range of expertise from materials' toxicology, risk assessment, life cycle assessment, circular economy and ethics in nanotechnology. Moreover, professionals working in sustainable nanofabrication require adequate infrastructures, skills, equipment, characterization and metrology that permit them to perform their activities to develop their technologies or products at best. Scattered information, lack of connection across the different communities or the difficulty of getting the right information about a related specific theme are just some of the issues that often prevent products from reaching the market. The EU H2020 project NanoFabNet is addressing these issues by setting up a self-sustaining one-stop-shop for all matters and concerns pertaining to sustainable nanofabrication. In this paper, the authors describe the development of the NanoFabNet database as part of the digital platform designed to collect, store, expert-curate and provide access to all matters pertaining to sustainable nanofabrication.

**Keywords:** Technology sustainability · Sustainable nanofabrication · Database development

## 1 Introduction

Nanotechnology is considered as one of the key enabling technologies of the 21st centuries. Over the last 30 years, the production and applications of nanotechnology and nanomaterials encountered a rapid growth bringing about fundamental changes in basic research as well as in many sectors of industry and our daily life. Its innovations have already helped to address several important societal needs, including the viability of


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 232–241, 2023.
https://doi.org/10.1007/978-981-19-9205-6_22

renewable energies, medical treatments and early detection systems, creation of more sustainable consumer products, and even the increase of agricultural productivity.

Nanotechnology makes use of the unique physical and chemical phenomena that occur at these small scales in the nanometer range, such as quantum and surface effects. Nanomanufacturing essentially connects the discoveries of the nanosciences and real-world nanotechnology products. It encompasses many processes from the design, manipulation and control of matter at the nanoscale to the manufacture of nanoscale materials, nanostructures, components, devices and complex system [1, 2]. For example, top-down nanofabrication approaches make use of lithography or etching processes to define structure dimensions, whereas bottom-up approaches use chemical synthesis to connect individual molecules into larger, functional building blocks [3].

Beyond the technical difficulties inherent in the production of these advanced technologies, there are also many issues related to their production and integration into complex and interoperable systems in a sustainable framework. The problems to be addressed in order to envisage the implementation of a real sustainable, industrial-scale nanofabrication are therefore very varied, but have the following point in common: the conditions for trust must be met between economic actors in the same value chain, between economic actors and public authorities, and finally with civil society.

### 1.1 Challenges of Technological Sustainability

Sustainability is a key-issue in an "age of sustainable development" demanding solutions to important environmental, social and economic problems [4–6]. There exists to date no universal definition for the term sustainability and a multitude of different concepts such as life cycle sustainability assessment, ethics, circular economy, green chemistry are associated to the topic of sustainability.

The complexity and multidisciplinary themes that need to be covered and considered to approach the topic of sustainable nanofabrication require a wide range of expertise, covering from toxicology and ecotoxicology to risk assessment and safety of nanomaterials and ethics in nanotechnology. A literature review [7] identified three sustainability areas relevant for nanotechnology and nanofabrication: (1) Environment, health & safety, (2) Life cycle sustainability and (3) Ethics and governance. The area "Environment, health & safety" addresses the requirements and available tools to conduct a full risk assessment for human and environmental health in alignment with existing EU regulation. The "Life cycle sustainability" area represents approaches for a holistic life cycle sustainability assessment with components coming from classical and social life cycle assessments as well as life cycle costing analyses. The third area "Ethics and governance" addresses approaches, tools and concepts dealing with the ethical and governance aspects in nanotechnology and nanomanufacturing.

However, the science and technology fields of sustainability and (nano) fabrication are still facing several major challenges: the existing separation between both fields, the increasing specialization within each field, and the geopolitical clustering of specialized communities and infrastructures as demonstrated by the in-depth bibliographic analysis of more than 1.2 Mio. Scientific publications from the areas of nanotechnology and sustainability (Friedrichs et al. 2022, publication in preparation).

### 1.2 Establishing an International Community for Sustainable High-Tech Micro- and Nanofabrication - the NanoFabNet Approach

The challenges described in previous sections, namely the fragmentation of the scientific disciplines with their individual thematic challenges as well as the geopolitical clustering of its expert communities clearly demonstrate the need for a central supportive system to bridge theses gaps and bringing the communities together. In this context, the EU H2020 coordination and support action NanoFabNet project (International Hub for sustainable industrial-scale nanofabrication, GA No. 886171) was set up with the aim to establish an international hub for sustainable nanofabrication. The central objective was to set up a consolidated, self-sustaining one-stop-shop collaboration platform for all matters and concerns pertaining to sustainable nanofabrication. This virtual collaboration space is offering strategic networking, up-to-date knowledge on research and standardization, skills development and access to EU services and infrastructures. The elaboration of the scientific challenges and strategic action plans, identification of key community needs' as well as the business plan development were supported by a number of stakeholder consultations and co-creation workshops.

The database described in this paper is at the core of this platform functioning as a "digital twin" to the NanoFabNet stakeholder community. The paper focusses on the design and implementation of the NanoFabNet database as central storage and structured access point to the collected and curated information of the project.

## 2 Approach for Building the NanoFabNet Database

This section describes the approach employed to conceptualize and set-up the NanoFabNet database. The process follows a classical approach with an initial requirement analysis to decide on the most fitting type of database system for the data to be captured followed by conceptualization, mapping and implementation steps (see Fig. 1).

(1) Requirement analysis for the content to be captured within the database
(2) Query analysis on the outputs of the database to decide on the most fitting database type
(3) Conceptual design of the database
(4) Mapping of the conceptual design to a schema of the chosen database system
(5) Creation of administrative surface for data entries
(6) Creation of interactive query interface & implementation of query language
(7) Integration small workflow for simple data curation

The requirement analysis was designed to be built on several pillars, namely the in-depth bibliographic analysis to map the existing ecosystem of actors and fields of interest within the communities of nanotechnology and sustainability (Friedrichs et al. 2022, publication in preparation), a benchmarking analysis of existing online platforms, data sharing and database concepts implemented within the fields of nanofabrication and sustainability complemented by stakeholder input collected during the NanoFabNet stakeholder engagement workshops conducted in 2020 and 2021 as well as by a number of conducted online surveys. The results of these pillars as well as the following database design and implementation steps are described in detail in the next section.

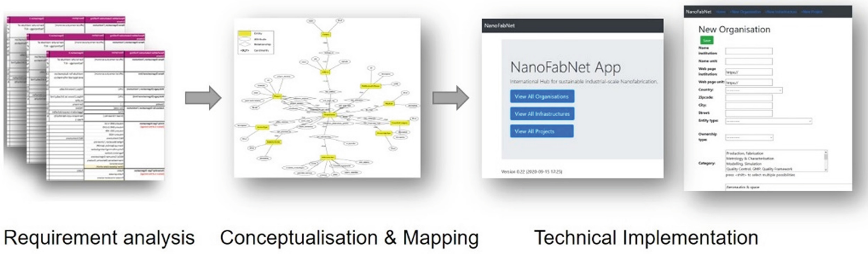



**Fig. 1.** Overview of the development process of the NanoFabNet database starting with requirement analysis, data model development and technical implementation of administrative surface for data entries, queries and user management.

## 3 Developing the NanoFabNet Database

This section is dedicated to describe in details the steps undertaken to develop the concept and subsequent implementation of a database in the frame of the H2020 project NanoFabNet following the methodology elaborated in Sect. 2.

### 3.1 Outlining Requirements for the NanoFabNet Database

Identifying potential data sources and content relevant to be captured within the database formed the starting point for the requirement analysis. In addition, the database should also provide the structure to capture the information generated within the different project activities such as the bibliographic analysis of scientific publications and other existing online data sources related to the communities of nanofabrication and sustainability, in-depth profiling of relevant actors, organizations and projects as well as relevant documents.

As a first step, a set of overarching questions to focus the requirement analysis on was elaborated across the experts involved in the project. The questions covered the identification of scientific disciplines and subdisciplines involved in nanofabrication & technology sustainability, most relevant technologies & applications, relevant actors/organizations/infrastructures and available competences, skills, technologies and resources. In the following, these questions were employed to direct the benchmarking analysis of existing platforms and for the stakeholder consultations conducted during two workshops and subsequent online surveys.

For the benchmarking analysis, a number of different online platforms, projects and related reports were screened on the approaches undertaken to collect and display relevant information, the type of information provided to the users and potential access modes to the available data coming both from the areas of sustainability and nanotechnology/nanofabrication. A selection of the analyzed platforms and data sources is shown in Table 1. A lot of information was publicly available related to European research infrastructures, e.g. the MERIL and CatRIS projects [8, 9], the compilation of project and organization profiles working the areas of Industry 4.0 and micro-nanotechnologies provided by the SNERGY project [10] or the collection and analysis of stakeholder organization information provided by the EU Key Enabling Technologies (KETs) Observatory [11, 12] or the NanoData - Nanotechnology Knowledge Database [13].

**Table 1.** Selection of analyzed online platforms and projects related to nanofabrication

| Platform name | Short description | Information provided | References & Links |
|---|---|---|---|
| NanoData - Nanotechnology knowledge database | Database coordinated by the European Observatory of Nanomaterials (EUON) on the current status of nanotechnology in the EU | Statistical data on R&D activities, organisations and products related to nanotechnology | https://nanodata.echa.europa.eu/, [13] |
| KETs observatories I & II | European online monitoring platform offering quantitative and qualitative information on the deployment of Key Enabling Technologies in the EU and worldwide | Statistical data, reports on EU KETs usage, Access to EU technology centres and innovation hubs | https://ec.europa.eu/growth/tools-databases/kets-tools/kets-observatory, [11, 12] |
| Projects MERIL-1, MERIL-2, CatRIS | Online portal for EU research infrastructures openly accessible | Catalogue of services and resources provided by EU Research Infrastructures and Core Facilities | https://portal.meril.eu/meril/, [8, 9], https://www.portal.catris.eu/home, [14] |
| SYNERGY Profiling IT Tool "SYNPRO" | Profiling tool for organisations and projects from the (nano)manufacturing sector created by the CE Interreg project SYNERGY | Competences, skills, experience track record, technologies, available infrastructures | https://synpro.e-science.pl/, [10] |

As a result of this benchmarking analysis, relevant information from the different sources was extracted, complied and categorized into three main data categories "organizations", "projects", and "infrastructures" relevant for the communities of sustainable nanofabrication. Next, a set of relevant data fields for each of the main categories to be integrated within the database was formulated and harmonized with the content to be collected from the different project activities (mapping, profiling). These entailed general information such as the official names, address details, web links, digital identifiers complemented by an in-depth profile describing the activity and industry sectors, provided services, available expertise, tools and equipment as well as references such as certifications, publications or project involvements.

The integration of the collected information then led to an initial conceptual model in which the various identified entities (organizations, infrastructure, projects,…), their attributes (name, URL,…), and their relationships between the entities were modeled. Cardinalities play an important role in the relationships. The cardinalities indicate the minimum and maximum number of other entities with which any given entity can have a concrete relationship. This also has a significant influence on the design of the relational schema. Figure 2 shows an extract of the conceptual model that has been created, in which the entity "organization" with a few selected attributes is at the center, along with the relationships to the other entities.

Each of the main entities (yellow squares) consists of a specific name and one or more attributes (ellipses). The relationships between the individual entities are depicted as diamonds and the cardinalities on top of the connecting lines describe the relationship between the two connected points. For example, the relationship "coordinates" between "organization" and "project" has the cardinalities <1,1> (project side) and <0,n> (organization side). This means that a project is coordinated by exactly one organization (minimum 1, maximum 1). On the other side, an organization can coordinate no project at all (minimum: 0) or multiple projects (maximum: n).

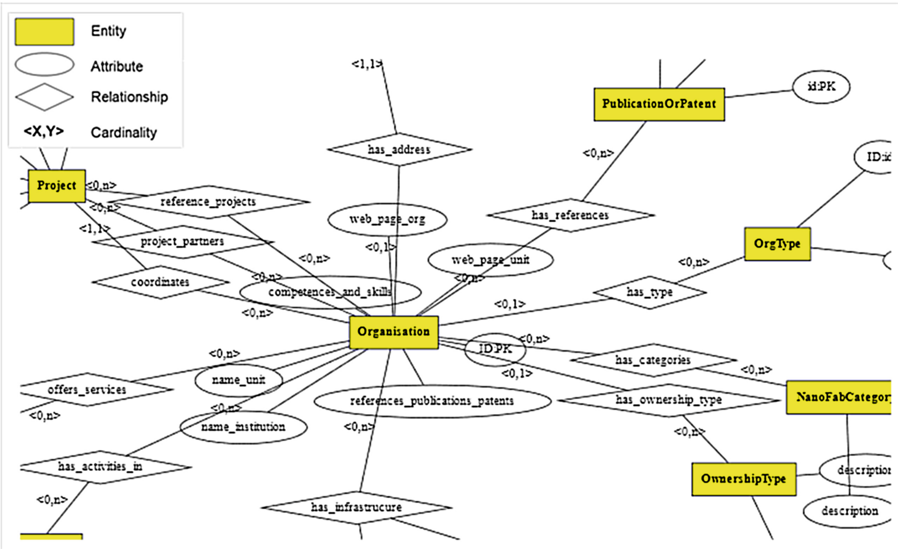
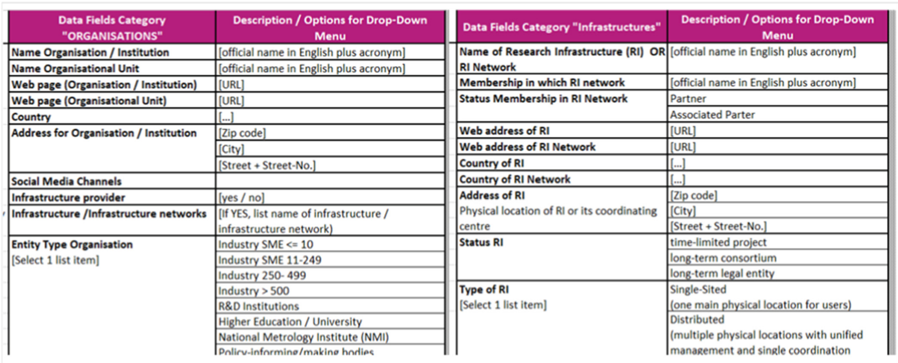



**Fig. 2.** Excerpt of the conceptual data model for the main category "organization". (Color figure online)

The outputs of this conceptual model were subjected to the stakeholder community in the course of two virtual workshops to collect feedback and tailor the initial concept to the actual needs of the communities of nanofabrication and sustainability. The experts coming from academia and industry active in the areas of sustainability and nanotechnology confirmed the relevance and necessity for such a one-stop-shop of information. Advice was given from the communities to integrate a "quality assessment" for the provided content, use the envisioned database content for targeted matchmaking and also to explore the option of integration data from existing data sources (open access, CC-by-licensing etc.).

As a next step, detailed Excel templates for each of the main categories organizations, projects and infrastructures were generated to serve as basis for the actual design and technical implementation of the database as well as for the data collection activities conducted by the project consortium (see Fig. 3).



| Data Fields Category "ORGANISATIONS" | Description / Options for Drop-Down Menu |
|---|---|
| Name Organisation / Institution | [official name in English plus acronym] |
| Name Organisational Unit | [official name in English plus acronym] |
| Web page (Organisation / Institution) | [URL] |
| Web page (Organisational Unit) | [URL] |
| Country | [...] |
| Address for Organisation / Institution | [Zip code] |
| | [City] |
| | [Street + Street-No.] |
| Social Media Channels | |
| Infrastructure provider | [yes / no] |
| Infrastructure /Infrastructure networks | [If YES, list name of infrastructure / infrastructure network) |
| Entity Type Organisation [Select 1 list item] | Industry SME <= 10 |
| | Industry SME 11-249 |
| | Industry 250- 499 |
| | Industry > 500 |
| | R&D Institutions |
| | Higher Education / University |
| | National Metrology Institute (NMI) |
| | Policy-informing/making bodies |

| Data Fields Category "Infrastructures" | Description / Options for Drop-Down Menu |
|---|---|
| Name of Research Infrastructure (RI) OR RI Network | [official name in English plus acronym] |
| Membership in which RI network | [official name in English plus acronym] |
| Status Membership in RI Network | Partner |
| | Associated Parter |
| Web address of RI | [URL] |
| Web address of RI Network | [URL] |
| Country of RI | [...] |
| Country of RI Network | [...] |
| Address of RI | [Zip code] |
| Physical location of RI or its coordinating | [City] |
| centre | [Street + Street-No.] |
| Status RI | time-limited project |
| | long-term consortium |
| | long-term legal entity |
| Type of RI [Select 1 list item] | Single-Sited (one main physical location for users) |
| | Distributed (multiple physical locations with unified management and single coordination |

**Fig. 3.** Extract of the developed Excel templates for data capture and NanoFabNet database conceptualization for the example categories "organizations" and "infrastructures".

### 3.2 Database Selection and Application Development

Based on the requirements analysis, a suitable database system as well as the language for implementing the application logic was selected. In this specific case, we decided to use a classic relational database (MySQL), as it covers all the requirements for the application. The implementation of the application logic was realized via the Python-based framework Django [15]. This framework supports rapid development and massively assists the user in the development of web-based applications, so that the developer can concentrate on the application logic and does not have to constantly reinvent the wheel [15]. For example, administration pages for creating, modifying and deleting records are automatically generated for all listed entities, without the developer having to take care of it. To test the database setup and functionalities, the data collected in separate excel templates (see Fig. 3) was used for an initial import employing a special Django plugin [16].

The characteristics of the established NanoFabNet database are summarized in the following Table 2. After successful data import, the database will be integrated into the virtual platform and access provided to external users in accordance to the developed business model and user management (e.g. public user or registered member).

**Table 2.** Overview on the key features of the implemented NanoFabNet database.

| | |
|---|---|
| Database scheme | The whole database consists of over 60 tables. This also includes the owner management tables and the management of access rights. The high number of tables is partly due to the fact that there are many n:m relationships between the entities, which are mapped to so-called relationship tables in relational databases. The user management is also used from an external Content Management System for Single-Sign On |
| Search facilities | A key aspect of the application is the search for suitable organizations, projects, etc. For this purpose, there is a combined full text/expert search, which supports a variety of query options. In addition, it is possible to mark individual entities with freely selectable tags, or to expand existing selection lists with your own entries, which can also be searched for |
| Interfaces | The interface consists mainly in a number of webpages. Besides that, a number of REST-API endpoints [17] exist, which allow a programmatic access to the content of the database. Actually, i.e. the single-sign-on mechanism is implemented as a number of REST-API endpoints |

## 4 Conclusions and Next Steps

The established NanoFabNet database described in this paper provides an essential part to the NanoFabNet platform and thereby to the NanoFabNet Hubs' business model. The hub is intended to function as a "connector of dots" providing relevant information on all matters pertaining to sustainable nanofabrication in a condensed and expert-curated format. As the main goal of this database is to facilitate for interested stakeholders a structured access to the collected and curated information from the projects' work program, it was important to iterate the concept and first implementation with the relevant stakeholders coming from academia and industry which are active in the areas of sustainability and nanotechnology. The feedback collected from the interactions with the stakeholders from the communities of nanotechnologies and sustainability clearly indicated a large interest in getting access to such a database as provided by the NanoFabNet project. The concept of self-governance of the content stored within the database to keep the information as up-to-date as possible was highly appreciated. Similarly, integrating already existing information from other sources such as the US NNCI, the EUROnanoLAB [18] or the GoFAIR implementation network "Go NanoFAB" [19] into the database was strongly supported by the communities. In this respect, FAIR principles [20] should be employed for data exchange and sharing with other databases. Already realized within the database is the recommendation of the open science community to use persistent digital identifiers for the captured data such as Orchid IDs for individuals or Research Organization Registry IDs for organizations.

The NanoFabNet database is providing one of the cornerstones to the implementation of the 2030 strategic roadmap for sustainable nanofabrication (NanoFabNet, in preparation). Raising awareness on sustainability, compliance with regulation and legislation, implementation of sustainability indicators and community engagement are some of the steps to be taken in order to establish and maintain a productive, collaborative community in the highly interdisciplinary field of "sustainable nanofabrication".

As briefly indicated in Sect. 1.2, one of the main goals and thus the next step is to launch the NanoFabNet Hub as a formally registered entity at the end of the project based on the developed business model and business plan which were done in alignment with the stakeholder consultations. The database described in this paper with its collected content will be providing an essential part of the developed business model, namely by providing the foundation (content) for the services to be provided to the stakeholders, members and external users within the EU and beyond. These services include access to relevant standardisation & harmonisation documents, curated safety-, ethics- and governance-considerations in the high-tech sector, expert supported matchmaking of sustainability opportunities or an international market place for R&I collaboration and B2B services.

**Acknowledgement.** This work was funded by the EU H2020 project NanoFabNet (GA No. 886171) and also supported by the Karlsruhe Nano Micro Facility (KNMFi, www.knmf.kit.edu), a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu) and under the Helmholtz Research Program MSE (Material Systems Engineering) at KIT.

## References

1. Cooper, K.P., Wachter, R.F.: Nanomanufacturing: path to implementing nanotechnology. Int. J. Nanomanuf. **9**(5/6), 540–554 (2013)
2. International Organisation for Standardisation (ISO), ISO/TS 80004–8:2020: Nanotechnologies — Vocabulary — Part 8: Nanomanufacturing processes, pp. 1–27 (2020)
3. Biswas, A., et al.: Advances in top-down and bottom-up surface nanofabrication: techniques, applications & future prospects. Adv Colloid Interface Sci **170**(1–2), 2–27 (2012)
4. Mulder, K., Ferrer-Balas, D., van Lente, H.: Chapter 1: what is sustainable technology?, In: What is Sustainable Technology? Perceptions, Paradoxes and Possibilities, Greenleaf Publishing, Routledge, pp. 1–7 (2011)
5. European Commission - Glossary Sustainable Development Homepage. https://ec.europa.eu/regional_policy/en/policy/what/glossary/s/sustainable-development. Accessed 30 Apr 2022
6. Sachs, J.D.: The Age of Sustainable Development. Columbia University Press, New York Chichester, West Sussex (2015)
7. NanoFabNet Consortium, Concepts & Disciplines of Sustainability in Nanotechnology & Nanofabrication, Public report, pp. 1–37 (2020)
8. MERIL-1 Project (FP7, GA No 262159), MERIL Data Field Definitions, pp. 1–8 (2002)
9. MERIL-2 Project (H2020, GA No 654296), A List of MERIL-2 RI Categories with Accompanying Descriptions, pp. 1–17 (2019)
10. Rosienkiewicz, M., Helman, J., Cholewa, M., Molasy, M.: SYNERGY project: open innovation platform for advanced manufacturing in central Europe. In: Burduk, A., Chlebus, E., Nowakowski, T., Tubis, A. (eds.) ISPEM 2018. AISC, vol. 835, pp. 306–315. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-97490-3_30
11. Van de Velde, E., et al.: Key Enabling Technologies (KETs) Observatory - Methodology Report, pp. 1–51 (2015)
12. Lengton, M., et al.: KETs Observatory Phase II - Methodology Report, Contract nr EASME/COSME/2015/026 (2017)

13. European Commission Directorate-General for Research & Innovation, et al.: NanoData landscape compilation: update report 2017. Publications Office of the European Union, Luxembourg, p. 192 (2018)
14. CatRIS Consortium and J. Spyrou, Deliverable 4.1: Mapping and gap analysis of service catalogues/portfolios, Public report, pp. 1–170 (2020)
15. Django Software Foundation Homepage. https://www.djangoproject.com/. Accessed 12 May 2022
16. Django import / export Homepage. https://django-import-export.readthedocs.io/en/latest/. Accessed 12 May 2022
17. Django REST framework Homepage. https://www.django-rest-framework.org/. Accessed 12 May 2022
18. EuroNanoLab Homepage. http://euronanolab.eu/. Accessed 30 Apr 2022
19. GO NANOFAB Implementation Network on Nanofabrication Homepage. https://www.go-fair.org/implementation-networks/overview/go-nanofab/. Accessed 30 Apr 2022
20. Wilkinson, M.D., et al.: The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data **3**(1), 160018 (2016)

# An Approach for Sustainable Knowledge Management and Policy Upstreaming for Industry4.0 in Central Europe

Clarissa Marquardt[1](✉), Amal P. Charles[1], and Steffen G. Scholz[1,2]

[1] Institute for Automation and Applied Informatics (IAI), Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany
clarissa.marquardt@kit.edu

[2] Karlsruhe Nano Micro Facility (KNMFi), Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, Germany

**Abstract.** The manufacturing industry is one of the major drivers and contributors to the success of the European economy. Within Central Europe, a large amount of high-value innovation know-how coming from academia and industry is clustered around the areas of advanced manufacturing and industry 4.0, two areas critical for maintaining Central Europe's competitive edge and high employment rate. However, lack of transparency in access to knowledge on the opportunities offered by Industry4.0 concepts and applications, insufficient cooperation and linkages between innovation actors within and between regions and countries as well as missing alignment of strategies and programs on a policy level are some of the challenges that the Central Europe innovation ecosystem is currently facing. In this paper, the authors describe the conceptualisation, realisation and outcomes of a series of stakeholder engagements workshops for the community-driven development of a sustainable comprehensive policy implementation framework for the areas of advanced manufacturing and industry4.0 in Central Europe.

**Keywords:** Policy upstreaming · Sustainable knowledge transfer · Advanced manufacturing · Industry4.0

## 1 Introduction

The European Union is the world's biggest exporter of manufactured goods, and is a global market leader for high-quality products [1]. In an analysis of the economy of 45 regions in the European Union, manufacturing contributed more than 30.0% of the non-financial business economy employment, largely concentrated in central Europe [2]. Central Europe's manufacturing sector is a fundamental component of the EU economy with a large amount of high-value innovation know-how in the area of advanced manufacturing and industry 4.0 (I4.0). These two areas are critical for maintaining Central Europe's competitive edge and high employment rate in this economic sector. In 2011, the concept of industry 4.0 was introduced at the Hannover fair as one of the key initiatives of the German high-tech strategy and subsequently integrated into a large number


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 242–251, 2023.
https://doi.org/10.1007/978-981-19-9205-6_23

of national and European innovation and research strategies [3]. This so-called fourth industrial revolution is based on the idea of merging the physical and virtual worlds through cyber-physical systems revolutionizing the production and the supply of goods and services, through the interconnection between products, processes and consumers. Usage of internet of things (IoT), artificial intelligence, cloud computing, autonomous robots, sensors, big data or advanced manufacturing are just some of terms associated with the development and implementation of I4.0 concepts.

The increasing advance of I4.0's facilitating/enabling technologies poses real challenges for industrial policy. A major concern is the potential displacement of labour caused by the spatially uneven distribution of capital-intensive I4.0 manufacturing technologies. This could yet again unduly favour more dynamic regions over peripheral ones, further amplifying regional socioeconomic divisions. [4]. The 2014–2020 European Union's Strategies for Smart Specialization-S3 already included certain aspects of related to Industry 4.0 and as of 2016 gained major importance with the digitizing European Industry Initiative of the European Commission [3, 5].

A comprehensive analysis conducted on the current policy and strategy ecosystem in Europe clearly demonstrated that as not all EU countries display the same level of development of their manufacturing industries, Industry 4.0-focused policies are also at different stages and paths. For an effective implementation, it becomes necessary to consider the technological potential of each region. For example, Germany, France and Spain were identified as EU leading countries with the most companies implementing I4.0 concepts. Differences in the strategic focus of national policies could also be observed, for example focusing in on research, development and innovation related to I4.0, the digitization of SMEs or the emphasis on education and professional training [3]. Academia and the private sector are required to work alongside public officials in a multi-stakeholder endeavor (triple-helix stakeholders) to provide expertise on the technologies which are being developed, focusing on their applications and potential [3, 5, 6].

To date, the Central Europe innovation ecosystem is still facing multiple challenges related to the integration and implementation of I4.0 concepts such as the lack of transparency in access to knowledge and markets, insufficient cooperation and linkages between the innovation actors in and between regions and countries. This translates also to the policy level where alignment and cooperation across the different programs is still missing on larger scale although the research & innovation smart specialisation (RIS3) strategy already includes certain components related to I4.0. Another challenge layer is added by the goals of the European Green Deal and the updated EU Industrial Strategy [7] to transform the EU into a modern, resource-efficient and globally competitive and resilient economy.

Recommendations taken from the policy analyses identify strategic support for SMEs, novel approaches for upskilling and reskilling of the European workforce and the promotion of collaborative enablers such as interregional partnerships or the digital innovation hubs (DIHs) as additional contributing success factors for the future implementation of Industry4.0 [3, 5, 8].

This paper describes the process of a community-driven development of a comprehensive policy implementation framework for the areas of advanced manufacturing and industry4.0 in Central Europe. The involvement of stakeholder groups from the triple-helix ecosystem will help to map the regional status quo, identify existing barriers and challenges within the context of I4.0 and develop practical policy implementation use cases to shape a comprehensive policy framework supporting the long-term and sustainable development of policy instruments for Central Europe manufacturing.

## 2 Methodology – the CEUP2030 Approach

The CE Interreg project CEUP 2030 (Central Europe Upstreaming for Policy Excellence in Advanced Manufacturing & Industry 4.0 towards 2030) was designed to generate a unique innovation system approach for regional & transnational policy making for the areas of advanced manufacturing (AM) and industry 4.0 (I4.0). The approach is driven by and well-embedded within in a regional, national and European stakeholder dialogue format to crosslink policies/strategies and programs for long-term validity. The project builds upon available outputs and results from excellent work delivered in the programming period 2014 to 2020 from the six H2020 / CE Interreg twin projects SISCODE, Spirit, DIH2, SYNERGY, 3DCentral and S3HubsinCE for the project implementation. A series of stakeholder interaction workshops (Policy Learning Labs, Network meetings, RIS3 round tables) with representatives from academia, industry and policy (triple-helix ecosystem [5]) are being employed to establish stable innovation networks for improved knowledge and resource exchange on the areas of AM and I4.0.

Within this context, the following four main topics of Intelligent Production Systems, Automation & Robotics, Smart Materials and Artificial Intelligence (CAMI4.0 topics) were recognized as the most strategic topics to be developed in the Central Europe area and formed the underlying categorization scheme for the developed networks and policy recommendations. The development of a comprehensive policy implementation framework for the four CAMI4.0 thematic areas is supported by the development of strategic policy pilot actions (flagship projects) showcasing practical examples for the adaptation of these concepts into the innovation ecosystem on a national and European level (see Fig. 1).

This paper focuses on the development of the trend and innovation networks and the evaluation of the workshop series focussed on the topic of Intelligent production system.


**Fig. 1.** Schematic overview of the CEUP2030 project concept with defined outputs and stakeholder interaction formats.

### 2.1 CAMI4.0 Trend and Innovation Networks

Stakeholder engagement, co-creation and mutual learning are some of the key components identified as excellent tools to realize the goals of the CEUP 2030 project and to provide overall benefits to the communities of advanced manufacturing and industry 4.0 [9, 10]. The established trend and innovation networks will cluster key stakeholders active in the four CAMI4.0 topics of intelligent production systems (IPS), automation & robotics (AR), smart materials (SM) and artificial intelligence (AI). At regional level, these digital working groups are comprised of key triple-helix-oriented stakeholders, who are critical for anchoring expertise and knowledge to target groups essential to the economic development of each region. This is complemented by inter-regional connections between these regional communities, championed by the partners of the CEUP 2030 project and fostered through the capabilities and competencies of the partner organizations and their network.

The main goals of the trend and innovation networks are (1) to generate improved knowledge and exchange on new technologies relevant for the CAMI4.0 topics; (2) to gather foresight on challenges and opportunities which emerge in the chosen technology areas, and across the territorial area's manufacturing sector including the EU Green Deal challenges; (3) to create a stable space to ideate, develop and implement new project ideas promoting and fostering interregional cooperation; and (4) to generate and gather professional input for direct and future-robust policy implementation.

### 2.2 Workshop Conceptualisation

Interactive workshop formats were selected as an established means of stakeholder engagement to directly involve and interact with the triple-helix representatives from academia, industry and policy-making working in the areas of advanced manufacturing and industry 4.0 [9]. The objective of the planned workshop series and stakeholder engagement was to raise awareness, provide knowledge and foster regional and transregional networking and cooperation within the communities of advanced manufacturing and industry 4.0 located in Central Europe.

The trend and innovation network meetings are designed as a set of 10 regional workshops complemented by one transregional workshop clustered around the predefined CAMI4.0 categories IPS, AR, SM and AI. The workshop concept follows a common structure of introducing the participants to the project activities, thematic focus and goal of the individual workshops followed by expert sessions showcasing the state-of-the-art and current challenges from an academic and industrial perspective for the respective CAMI4.0 topic. The subsequent discussion session is intended to facilitate information exchange between the participants to openly discuss about the presented topics, sharing the individual perspectives and challenges and identifying key facts to be considered for the projects' follow-up actions such as the development of flagship use cases for development of the policy strategies.

The outcomes of the workshops are being used to concretise the current state of development, challenges and opportunities of the CAMI4.0 topic of intelligent production systems also in relation to the sustainability goals of the EU Green Deal which ultimately will contribute to the development of the corresponding flagship projects and overarching policy implementation framework. A comprehensive feedback form is used to collect information on the workshop focussing on participants profiles, workshop content, key outcomes and lessons learnt from the organisers and participants perspective complemented by input generated from peer review interviews with selected workshop participants. This approach represents the summary of lessons learnt and best practices exploitation of stakeholder engagement formats as a result from the output analysis conducted for the selected six H2020 / CE Interreg twin projects.

## 3 Workshop Results

The results presented in this section will focus solely on the input generated from the trend and innovation network workshops focusing on the CAMI4.0 topic of Intelligent production systems (IPS). The evaluation of the workshop and impact assessment is focusing on the content provided to the attending triple helix stakeholders followed by the major outcomes of the workshop and derived recommendations for the further strategy development of the topic of IPS.

### 3.1 Workshop Stakeholder Engagement

In total, the conducted 11 virtual workshops on the topic of intelligent production systems accounted for 320 attendees. The participants represented R&D organizations, universities, large enterprises, SMEs, business support organizations, industry clusters and policy makers thus covering the full spectrum of the triple-helix stakeholders. 58% of the participants came from industry, 24% from higher education & research, 16% are working for business support organizations and only 7% represented the group of policy-makers/policy-influencing organization. This distribution already illustrates the high importance of the topic of IPS for industry and that involving stakeholders with a policy background is important but not always easy to achieve.

### 3.2 Workshop Content Analysis

The workshops effectively introduced the participants to the topic of intelligent production systems with its subtopics smart & sustainable manufacturing, production in the domain of big data, additive manufacturing-based hybrid process chains and scalable flexible manufacturing. An overview on the current ecosystem at regional, national and European levels was presented highlighting the progress achieved and main challenges to be overcome. The expert presentations gave insights into new technical and scientific developments and challenges regarding the application of IPS innovative solutions. Sharing of best practices and showcasing of current initiatives on ongoing IPS solutions allowed the participants to see how to overcome or cope with their individual challenges.

When looking at the predefined subtopics, the majority of the expert presentations focused on Additive Manufacturing based hybrid process chains, whereas smart & sustainable manufacturing or scalable flexible manufacturing were addressed to a lesser point. For Additive Manufacturing based hybrid process chains, 3D and 4D printing technologies were addressed as well as current developments for the usage of robots in modern manufacturing settings presented. Within smart & sustainable manufacturing, the expert talks focused on sustainability in mass production or on approaches for energy saving and reducing light pollution.

### 3.3 Workshop Key Outcomes

The conducted virtual workshops on the CAM4.0 topic of intelligent production systems successfully launched the regional trend innovation networks of triples helix stakeholders creating a space for knowledge exchange, to discuss and share trend and innovation foresights on the targeted topics well as foster networking and potential collaboration within the networks. The main outcomes can be clustered into the following five categories:

(1) **Identification of regional expertise and competences**
The expert talks, round tables and guided discussion sessions provided the attending triple helix stakeholder community with a better understanding of the full ecosystem for the topic of IPS. The mapped expertise, knowledge transfer and sharing of best-practices should enable the networks to fulfill their initial goals of forecasting trends, answering existing need and challenges in these topics as well as fostering collaboration on a regional and interregional level. Emphasis should be put on identifying research and innovation priorities for IPS on a regional level to create a comprehensive map for the Central Europe region. As of now, relevant stakeholders from the triple helix ecosystem are not yet effectively connected and there is a need to create better understanding on the possibilities and capabilities offered by IPS solutions.

(2) **Awareness of IPS impacts at industrial level**
The sharing of best practices specifically focused on industrial ecosystems gave a tangible level of concreteness to innovative proposed solutions, attracting SMEs and enterprises to invest on the topic. The triple-helix exchange format also presented representatives from public administration and academia with the opportunity to understand the real needs of industries and to create innovation supporters out of them. The sharing of best practices amongst industry representatives was evaluated as very positive supporting the development of mutual leaning platforms to foster such exchange formats.

(3) **Raise awareness on key challenges in the IPS sector**
The involvement of expert panels did create a better understanding of the current ecosystem regarding IPS technologies together with the current technological key challenges. In addition, the need for general skills and competence development within IPS as well as a specific support for SMEs in their transition towards IPS models were highlighted. Sustainability as one of the EU Green Deal key challenges was surprisingly underrepresented in the discussions that require further attention for implementation at industrial scale.

(4) **Awareness on current opportunities**
Answering the existing market needs requires the involvement of all triple helix stakeholders. Transition towards IPS needs dedicated funding programs for which communication with policy-stakeholders on current opportunities, effectiveness of existing IPS solutions and current gaps is key. Similarly, developers and end users need support in navigating the funding landscape of available policy instruments. For representatives from policy-making it is important to better understand the current technologies to mobilize funds and create novel funding opportunity. However, different communication formats and materials are needed to effectively interact with this stakeholder group, e.g. focusing on success stories and practical examples within a personal exchange format.

(5) **Creation of active networks and communities**
The workshops effectively addressed the communities' [1] needs for networking, knowledge exchange and discussion forums for such highly specialized topics like IPS. Virtual formats allow for the engagement of larger number of stakeholders with a wider geographical reach and direct feedback collection by different online tools. However, effective networking, open talks and direct information exchange are some of the main issues virtual events are facing compared to physical meetings. Professional support in connecting technology providers with technology receivers is needed to foster the adaptation of IPS solution. Support offered by digital innovation hubs, cluster initiatives or other regional networks should be further exploited in this context.

### 3.4 Recommendations and Next Steps

Based on the outcomes collected from the IPS trend and innovation network workshops and described in Sect. 3.3, the following set of recommendations for the policy implementation framework can be formulated:

Firstly, there is a great interest in the topics of advanced manufacturing and industry 4.0 as was demonstrated by the large number of stakeholders attending the CAMI4.0 trend and innovation network series. Such exchange formats should therefore be fostered to enhance understanding and identify key partners to build new cooperation [1, 5]. This knowledge exchange will become even more important in the context of overarching challenges such the sustainability and circular economy goals of the EU Green Deal and how to implement these on a practical level.

Secondly, SMEs in particular were identified to need additional support in their transition towards Industry 4.0 which reflects the priorities set within the update of the EU's Industrial strategy 2020 [7]. Here IPS solutions play an essential role, as SMEs have a lot to gain by implementing Industry 4.0 concepts but also a lot to lose as they have less resources than bigger companies [11, 12]. A first step would be to support SMEs with easily accessible test-before-invest approaches. Via access to such testing facilities, the SMEs can gather insight into the actual working of these intelligent production systems and explore how to functionally adopt new solutions before investing. This entails exploring the added-value that additive manufacturing techniques are offering, understanding where flexible production systems can be implemented to improve their efficiency, and how to utilize big-data or intelligent data-mining for advancing their own business model [13]. This need for strategic support for SMEs as well as novel approaches for re- and upskilling is already being reflected in a number of national or European innovation strategy document [14, 15].

Cooperation and collaboration initiatives have been intensified to be crucial for the further development and adaption of the IPS concepts for the manufacturing industry. Exchange formats such as the trend and innovation networks meetings described in this paper should be implemented on a regular basis to create a common space for knowledge exchange, discussions on current projects and initiatives and novel developments related to best practices on IPS. Complementary virtual and physical meeting formats should be developed to fully involve the audience and address the individuals' needs and mutual learning process. This should enhance the integration of a wider audience and therefore should emphasize the connection between key stakeholders through a better understanding of the ecosystem. Current examples for such collaborative enablers are the digital innovation hubs, cluster initiatives or the national platforms for Industry4.0 as well as the policy learning platform provided by the Interreg Europe program [16].

To accelerate the changing process, it is crucial to not only raise awareness on potential funding opportunities but also to develop appropriate funding schemes to support SMEs in their digital transformation and in their appropriation of IPS solutions. Again, communication and exchanges are key to enhance understanding between the stakeholders and especially between different types of the triple helix stakeholders such as decision makers and SMEs. Communication approaches should be tailored to the needs of the different interest groups providing tangible examples such as success stories, flagship projects in particular for policy makers or best practice examples for industrial representatives.

Finally, to support the changing process, it is key to develop understanding and therefore competencies of individuals regarding IPS and Industry 4.0 topics. Therefore, offers should be developed and awareness should be raised on these services to accelerate the process. It is therefore key to enhance cooperation between service providers and SMEs to enable SMEs to be aware of what is available and for service providers to identify the market needs.

## 4 Conclusions and Next Steps

This study elaborated on the conceptualization and realizations of series of stakeholder engagements workshops dedicated to the CAMI4.0 topic of intelligent production systems as means to formulate community-driven recommendation for a policy implementation framework. The interregionally-connected technology foresight networks were successfully established thereby raising awareness on the challenges and opportunities offered by the CAMI4.0 topic of intelligent production systems as well as initializing new collaborations. The collected insight and feedback provided valuable input to the preparation of the IPS policy implementation framework.

One of the IPS subtopics was specifically targeting smart & sustainable manufacturing which was surprisingly underrepresented in both the expert contributions as well as the discussion points raised by the different stakeholder networks. This lack of interest could be either due a lack of knowledge and understanding or to a lesser priority compared to the development of new technologies and innovation. This gap should be addressed for both academic and industrial stakeholders to create a common understanding on the benefits and approaches for this green and sustainable transformation process supported by strategic actions from the policy making sector.

A next step involving the established regional networks will be the joint ideation and realization of strategic policy pilot actions (flagship projects) to provide tangible examples for the triple-helix stakeholder communities on the implementation possibilities of the CAMI4.0 topics. This combined approach of community driven development of best practice examples and policy strategies will ensure a sustainable transfer of knowledge and outputs generated within the CEUP2030 project into current and future project ideas and facilitate communication of regional/national needs and strategy focus for policy makers to shape the upcoming innovation programs.

**Acknowledgements.** This work was funded by the Interreg Central Europe program and carried out in the frame of the CEUP2030 project (Grant Agreement CE1662). The authors gratefully acknowledge the work and contribution of the project partners Krakow Technology Park, Profactor GmbH, Association Industry 4.0 Austria, Fraunhofer Institute for Machine Tools and Forming Technology, Lombardy Intelligent Factory Association, SIIT S.c.p.a. Intelligent Integrated Systems Technologies, Pomurje Technology Park, Pannon Business Network Association and the Croatian Agency for SMEs, Innovations and Investments towards the realization and documentation of the trend and innovation network workshops This work was also supported by the Karlsruhe Nano Micro Facility (KNMFi, www.knmf.kit.edu), a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu) and under the Helmholtz Research Program MSE (Material Systems Engineering) at KIT.

## References

1. ManuFUTURE High-Level Group, ManuFUTURE Strategic Research and Innovation Agenda (SRIA) 2030, Report from ManuFUTURE High-Level Group, December 2019 Final version, pp. 1–48 (2019)
2. EuroSTAT Homepage. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Main_Page. Accessed 30 Apr 2021
3. Teixeira, J.E., Tavares-Lehmann, T.C.P.: Industry 4.0 in the European union: Policies and national strategies. Technol. Forecast. Soc. Change, **180**, 121664 (2022)
4. Barzotto, M., et al.: Smart specialisation, industry 4.0 and lagging regions: some directions for policy. Region. Stud. Region. Sci. **7**(1), 318–332 (2020)
5. Lepore, D., Spigarelli, F.: Integrating Industry 4.0 plans into regional innovation strategies. Local Econ. **35**(5), 496–510 (2020)
6. Galvao, A., et al.: Triple helix and its evolution: a systematic literature review. J. Sci. Technol. Policy Manag. **10**(3), 812–833 (2019)
7. European Commission: Questions and Answers on the update of the 2020 Industrial Strategy (5 May 2021). https://ec.europa.eu/commission/presscorner/detail/en/QANDA_21_1885. Accessed 30 Apr 2022
8. Tvaronaviciene, M., Burinskas, A.: Industry 4.0 significance to competition and the EU competition policy: a literature review. Econ. Sociol. **13**(3), 244–258 (2020)

9. Fauth, J., Marquardt, C., Di Bari, G., Raule, N., Ronco, J.L., Scholz, S.G.: Stakeholder-driven conceptualization of open innovation approaches in the SYNERGY project. In: Scholz, S.G., Howlett, R.J., Setchi, R. (eds.) Sustainable Design and Manufacturing 2020. SIST, vol. 200, pp. 307–317. Springer, Singapore (2021). https://doi.org/10.1007/978-981-15-8131-1_28
10. Rosienkiewicz, M., Helman, J., Cholewa, M., Molasy, M., Krause-Juettler, G.: Analysis and assessment of bottom-up models developed in central europe for enhancing open innovation and technology transfer in advanced manufacturing. In: Scholz, S.G., Howlett, R.J., Setchi, R. (eds.) Sustainable Design and Manufacturing 2020. SIST, vol. 200, pp. 119–128. Springer, Singapore (2021). https://doi.org/10.1007/978-981-15-8131-1_11
11. Moshiri, M., et al.: An Industry 4.0 framework for tooling production using metal additive manufacturing-based first-time-right smart manufacturing system. Procedia CIRP **93**, 32–37 (2020)
12. Charles, A., Hofer, A., Elkaseer, A., Scholz, S.G.: Additive manufacturing in the automotive industry and the potential for driving the green and electric transition. In: Scholz, S.G., Howlett, R.J., Setchi, R. (eds.) KES-SDM 2021. SIST, vol. 262, pp. 339–346. Springer, Singapore (2022). https://doi.org/10.1007/978-981-16-6128-0_32
13. Mueller, T., et al.: Eight weeks later—the unprecedented rise of 3D printing during the COVID-19 pandemic—a case study, lessons learned, and implications on the future of global decentralized manufacturing. Appl. Sci. **10**(12), 4135 (2020)
14. Ministerium für Wirtschaft Arbeit und Wohnungsbau Baden-Württemberg, : Innovationsstrategie Baden-Württemberg (Fortschreibung 2020): Stuttgart, pp. 1–80 (2020)
15. European Commission: European Regional Development Fund - Policy 2021–2017. https://ec.europa.eu/regional_policy/en/funding/erdf/. Accessed 30 Apr 2022
16. Interreg Europe Policy Learning Platform - A Platform for policy advice, knowledge sharing and networking, https://www.interregeurope.eu/policy-learning-platform. Accessed 30 Apr 2022

# A Reinforcement Learning Approach to Powertrain Optimisation

Hocine Matallah[1](✉), Asad Javied[1], Alexander Williams[1], Ashraf Fahmy Abdo[1,2], and Fawzi Belblidia[1]

[1] Advanced Sustainable Manufacturing Technologies (ASTUTE 2020), Swansea University, Swansea SA1 8EN, UK
h.matallah@swansea.ac.uk

[2] Department of Electrical Power and Machines, Helwan University, Helwan 11795, Egypt

**Abstract.** A strategy to reduce computation time and improve minimisation performance in the context of optimisation of battery electric vehicle power trains is provided, motivated by constraints in the motor manufacturing business. This paper proposes a holistic design exploration approach to investigate and identify the optimal powertrain concept for cars based on the component costs and energy consumption costs. Optimal powertrain design and component sizes are determined by analysing various powertrain configuration topologies, as well as single and multi-speed gearbox combinations. The impact of powertrain combinations on vehicle attributes and total costs is investigated further. Multi-objective optimisation in this domain considers a total of 29 component parameters comprised of differing modalities. We apply a novel reinforcement learning-based framework to the problem of simultaneous optimisation of these 29 parameters and demonstrate the feasibility of this optimisation method for this domain. Our results show that, in comparison to single rear motor setups, multi-motor systems offer better vehicle attributes and cheaper total costs. We also show that load points with front and back axle motors may be shifted to a greater efficiency zone to achieve decreased energy consumption and expenses.

**Keywords:** Machine learning · Reinforcement learning · Powertrain configuration · Neural networks · Multi objective optimisation · Vehicle system simulation

## 1 Introduction

Electric vehicles (EVs) are a major technology in next-generation mobility seeking to fulfil global emission reduction objectives including the Paris Agreement [1] and European Union (EU) targets [2]. In the late 1970s, the EU established a link between air quality and automotive emissions, culminating in pollution-control legislation. The Euro criterion for passenger cars was enacted in 1992, and established a pollution concentration ceiling [3]. Over time, these standards have become stricter [4], and forced industry to adopt more efficient car powertrains. This may be seen in the growing market share


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 252–261, 2023.
https://doi.org/10.1007/978-981-19-9205-6_24

of hybrid electric vehicles (HEVs) and predictions of an increase in sales over the next decade [5].

The automotive industry considers engine optimisation to be one of the most promising methods for reducing the environmental impact of urban transportation, improving air quality, and meeting emissions objectives. Compared to classic internal combustion engines (ICE), electric motors used in EVs are significantly more efficient, with peak efficiency of a typical electrical machine for these applications oscillating around 95%. Additionally, Battery Electric Vehicles (BEVs), in comparison to classic ICE vehicles, are simple and easy to operate with a BEVs possessing far fewer moving parts and a simpler powertrain architecture than a conventional gasoline-powered vehicle, comprised only of a high voltage battery, an electric motor with a power electronics controller, and a single speed gearbox. Currently, there is a great demand from Original Equipment Manufacturers (OEMs) in the automotive industry together with its partners and suppliers to reduce the costs associated with design, manufacturing, and assembly of BEVs.

### 1.1 Related Work

The powertrain is a vehicle subsystem consisting of an electric motor, battery, power electronics, and transmission that has substantial impact on a vehicle's energy consumption and performance, including its total range. To improve the efficiency of the powertrain, research has been conducted at various levels, ranging from component improvements [7]–[10] and topology/structure [11, 12] to vehicle concept level optimisation [13]. Kivekäs et al. [14] investigated different powertrain configurations for electric city buses and showed differences in the energy consumptions of up to 11%, in comparison to a single rear motor configuration. However, the influence of component sizing was not investigated and only five powertrain configurations were compared. Pathak et al. [15] conducted a holistic design exploration to identify optimal powertrain configurations for electric city buses. The results showed that the overall efficiency of the powertrain is strongly influenced by the load points arising from the driving resistances. The powertrain structure, transmission design, and motor sizing were thus varied to identify concepts where the load points were shifted to regions of a higher efficiency. However, a constant passenger load was used, which could have resulted in imprecise estimates of the load points, and thus led to improper design of the powertrain concept. Further investigations addressed the design of the required charging infrastructure [6] and its respective impact on the battery capacity of the bus [6, 16]. Although vehicle concept optimisation and powertrain concept optimisation represent a state of research for electric passenger cars and enable the identification of an optimal solution regarding design objectives across multiple criteria [16], there is limited research on optimising vast ranges of design parameters. At this moment, industry, research centres and government are combining efforts to address the key bottlenecks of this complex engineering challenge.

### 1.2 YASA Powertrain Model

YASA is a British manufacturer of electric motors and motor controllers that is playing a growing role in meeting strict emissions targets being set globally across a wide range of industries and requirements for greater efficiency through electrification. A well-known challenge in BEV production is optimisation of the powertrain, a highly complex problem due to the multitude of potential optimisation variables and conflicting design objectives. Solutions to this problem usually leverage overly simplified vehicle/powertrain models or have produced optimisation processes with slow convergence and uncertainty as to whether a true global optimum has been reached. In this context, efforts of minimising the cost of all relevant electric powertrain components from battery, inverter, electric machine to gearbox are a top priority. Whilst minimising these elements, a range of performance constraints such as minimum range, top speed and acceleration time must be all simultaneously met for valid solutions. Some examples of optimisations are presented in [7, 11, 12, 17]. In such cases, a computer-based simulation tool is necessary to identify minimal-cost system designs taking all interactions into account while reducing the necessary engineering effort. High system complexity prevents a careful consideration of all relevant correlations without the support of numeric simulation tools. Consequently, it is often exceedingly difficult to find a minimal cost system design for given requirements at vehicle level by a top-down system design process.

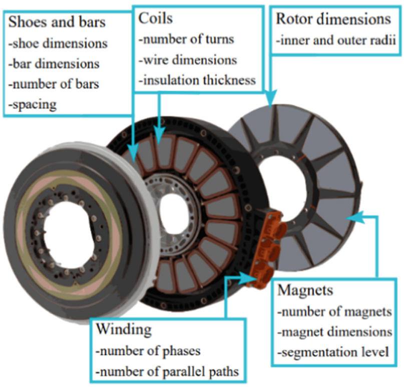



**Fig. 1.** Illustration of YASA topology with some of the key variables and variable groups marked [16]

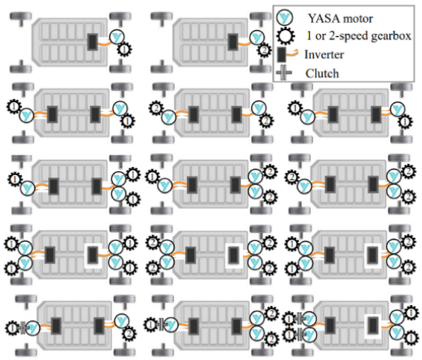



**Fig. 2.** Different powertrain configurations used as one of the discrete variables in the optimisation [16]

## 2 Literature Review on Powertrain Optimisation

Literature on optimisation of BEVs and HEVs parts is substantial. Numerous minimisation approaches have been proposed, ranging from component sizing [5] to low noise and lightweight design optimisation [13] but implementations focusing on powertrains have drawn the most attention because it is the module whose components have the greatest impact on the overall vehicle cost structure [18]. According to [11], the battery accounts for most of the expenditures associated with EVs. [18] provides details on the prices of battery manufacture for EVs, stating that battery costs alone can amount for up to one-third of overall vehicle expenditures. [17] suggested using a Genetic Algorithm (GA) to optimise two-speed powertrain characteristics of electric cars. The key performance characteristics of the drive motor and the gear ratios of the two-speed transmission were optimised. For the vehicle optimisation model and the GA optimiser, the authors recommended using a combination of MATLAB® and Simcenter Amesim®. A multi-objective genetic algorithm (MOGA) was introduced in [14] to optimise the HEVs powertrain for optimal energy efficiency. In this scenario, the goals were to reduce fuel consumption, increase battery state of charge, and maintain vehicle performance during the driving cycle. A MOGA investigates the important trade-offs between many goals, resulting in a group of equally valid answers known as Pareto front solutions or non-dominated solutions [13, 19], rather than a single solution. The highest speed, battery state of charge, internal combustion engine power, and other decision factors were employed in this optimisation. Similarly, [3] proposes modelling the powertrain of a HEV conversion system while considering multiple vehicle usages and using a multi-objective optimisation technique to configure the conversion system's important components. The decision factors for powertrain design are optimised using a GA-based optimisation technique. While [3, 9] concentrated on HEVs, [20] discussed global parameter optimisation of BEVs' dual-drive powertrain system. A MOGA was also employed, but this time the vehicle's acceleration time and driving mileage were used as indicators of dynamic and economic performance in the double-objective function. Torquato et al. [16] used the MATLAB®/Simulink platform to create a vehicle simulation model that was used for simulation.

## 3 YASA Vehicle Model

Electric powertrains are relatively new in the automotive industry and designing economical, efficient, and high-performance powertrains is challenging. Different engine architectures are frequently used in BEVs to minimise cost while satisfying essential performance limitations. As bigger vehicles must deal with more inertial (acceleration) and rolling resistance, efficiency and vehicle mass are intimately linked [2], justifying the industry's focus on component mass. Eliminating 1 kg of weight from a subsystem does not immediately correlate to a 1 kg reduction in vehicle mass due to mass decompounding [19]. Lighter bodies necessitate a lighter chassis, which in turn necessitates a smaller, more efficient powertrain, resulting in greater mass decompounding. Consequently, deriving the ultimate weight is an incremental process. Due to mass decompounding, the only method to obtain an optimal vehicle is adopting a system approach, where all powertrain components are optimised collectively rather than separately. The plethora of complexity layers is challenge when using system level optimisation, with each subsystem's variables and constraints adding up to a huge number of independent variables and constraints in a new, much larger optimisation issue.

The YASA Vehicle Model (YVM), developed in MATLAB®, was created to compute a powertrain's output performance in the context of a vehicle of interest. In earlier work [16] a Machine Learning (ML)-based Vehicle Model (MLVM) was developed to reduce execution time. In this work, we derive a new neural network (NN) model to approximate the YVM using similar techniques. The model was created by randomly selecting independent input variables within each variable's respective upper and lower bounds, running these inputs through the YVM to generate the corresponding dependent output variables, recording the inputs and outputs in a dataset, and then using this dataset as the basis for training the NN model with supervised learning. This data set contained a total of 164k observations, each comprised of values for 35 variables with 23 inputs (motor 1 and motor 2 related variables, plus others) which are a mixture of 14 continuous and 9 categorical variables, and 12 outputs (6 cost related and 5 other variables). A summary of these variables is given in Table 1. Illustrations of these parameters as they relate to the physical powertrain are also given in Fig. 1.

**Table 1.** Input and output variables of the dataset

| Input variables | | |
|---|---|---|
| Motor 1 | Motor 2 | Other |
| flatToFlatLength<br>innerHubDiameter<br>magnetThickness<br>barLength<br>copperWidthInd<br>copperThicknessInd<br>windingConfig_parallelPaths<br>peakCurrentDensity<br>inverterId | flatToFlatLength<br>innerHubDiameter<br>magnetThickness<br>barLength<br>copperWidthInd<br>copperThicknessInd<br>windingConfig_parallelPaths<br>peakCurrentDensity<br>inverterId | axle1_gbxRatios_1<br>axle1_gbxRatios_2<br>axle2_gbxRatios_1<br>axle2_gbxRatios_2<br>powertrainConfigId |

| Output variables | |
|---|---|
| Cost | Other |
| Battery<br>Gbx<br>motorBaseline<br>magnet<br>inverterBaseline<br>Switch<br>total | WireSelection1<br>WireSelection2<br>accelTime0_60<br>topSpeed<br>nFailedPoints |

## 4 Reinforcement Learning Framework

Reinforcement Learning (RL) is a Machine Learning paradigm that depicts optimisation issues as an agent interacting with its surroundings to attain a goal. The environment responds to the agent's activities by presenting new states and delivering a scalar numerical reward signal that represents the current state's favourability to the agent [20]. The agent learns to optimise its received reward over time and via repeated exploration of the environment by learning the best action to take in every given environment condition. The agent and environment interact in a sequence of discrete time steps, $t = 0, 1, 2, 3, \ldots$. At each time step t, the agent receives a representation of the environment's state, $s_t \in S$ as an observation $o_t$, and selects action, $A_t \in A(s)$. One time step later, the agent receives a numerical reward, $r_{t+1} \in R$ and finds itself in a new state $s_{t+1}$. The state-of-the-art formalises RL tasks as sequential choice problems as a Markov Decision Process (MDP) [21]. MDPs have been shown to be a versatile abstract model for framing optimisation problems, and most of the research focuses on solving RL problems within the setting of an MDP [22]. A MDP is a 5-tuple $\{S, A, P, R, \alpha\}$ with state-space S, action-space A, transition dynamics P, expected immediate reward R, and discount factor $\alpha$. The agent in an MDP performs an action $a_t$ in state $s_t$, earns a reward ($r_{t+1}$), and then transitions to the next state $s_{t+1}$ using the transition dynamics $P(s_{t+1}|s_t, a_t)$.

Our work proposes incorporating our MLVM as the basis of a RL environment in which an agent seeks to derive a feasible powertrain design and minimise its cost. We propose a MDP in which states are defined by the configuration of input parameters and subsequent output parameters from the YVM / MLVM as shown in Table 1, actions involve selecting a new set of input parameters to the model, and the reward is calculated based on meeting the constraints for a feasible powertrain configuration and the overall cost. A software RL environment was written according to this MDP and incorporating the MLVM to serve as a test-bed for applying RL optimisation techniques in the EV powertrain optimisation domain. We subsequently apply a deep RL approach to solving this environment using dual NN models trained via an actor-critic method implemented in PyTorch [23]. We discuss the tuning of this model and the derivation of a suitable algorithm below.

## 5 Results

Experimental work was conducted to tune the new MLVM model discussed in Sect. 3 and determine the effectiveness of the RL framework for EV powertrain optimisation defined in Sect. 4, the results of which we present here. Firstly, we study the relationship of how each input parameter affects the total cost output. Then, we analyse the performance of our MVLM model by applying batch vs non-batch normalisation (BN) during training. After this, we tune the learning rates for the policy and value networks used in the A3C and GAE RL algorithms. Finally, we compare A3C and GAE methods for a single case scenario from the vehicle configuration map.

### 5.1 Feature Importance

There are many input parameters that need to be defined in a powertrain design as shown in Table 1. A study was undertaken to determine which parameters most significantly affected the total cost of the powertrain, which directly correlates to the given reward in our RL environment. A feature importance simulation revealed that powertrain configuration, variations of which are shown in Fig. 2, is the most significant contributor to total cost as shown in Fig. 3. The bearing on overall cost by other parameters is smaller in comparison but still important, especially when considering that the powertrain configuration may be fixed in some instances due to other requirements.

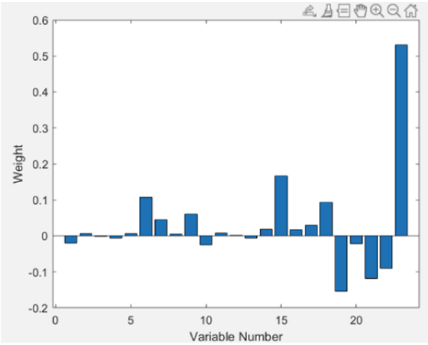



Fig. 3. Weighting of each input variable on the output, total cost

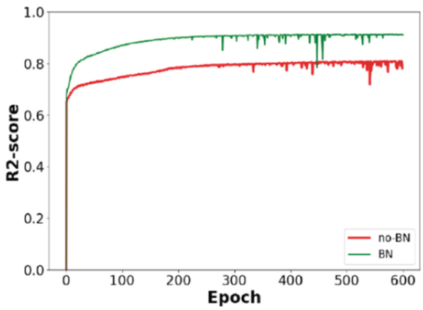



**Fig. 4.** R2-score for the total cost: Batch Normalisation (BN) vs Non-Batch Normalisation (No-BN) Batch Normalisation vs Non-Batch Normalisation

**Table 2.** Policy and value networks learning rates

| Learning rate configuration | Policy (Actor) | Value (Critic) |
|---|---|---|
| ***α-1*** | $10^{-2}$ | $10^{-2}$ |
| **α-2** | $10^{-3}$ | $10^{-3}$ |
| **α-3** | $10^{-4}$ | $10^{-3}$ |
| α-4 | $10^{-5}$ | $5.6*10^{-4}$ |

## 5.2 Batch Normalisation vs Non-batch Normalisation

To improve the accuracy of the MLVM described in Sect. 3, we compared the effects of BN and non-BN on model accuracy as depicted in Fig. 4. The input scaling is done with the tanh-estimator [24]. In this case, an optimiser learning rate (α) of $10^{-3}$ is employed. Batch normalisation has a significant impact on the learning process, as seen from the R2-score of total cost in Fig. 4. When BN is disabled, the r2-score for battery, total, and topSpeed is much lower at around 0.52, 0.82, and 0.78, respectively, compared to 0.80, 0.91, and 0.92 when BN is enabled. Therefore, BN is selected for construction of the NN model.

## 5.3 Effect of Varying the Learning Rate for Policy & Value Networks

There are many hyperparameters to tune in RL and for the A3C algorithm (PyTorch implementation [23]), however, learning rate (α) is one of the most significant parameters that influences the convergence of RL-trained NN models and so we focus on identifying suitable α for training our policy and value networks. A set of four distinct α configurations are used for the policy and value networks, given in Table 2. Of these, the smallest α set (α-4) shows slower convergence as shown in Fig. 5. The highest rewards are achieved in the least time with convergence stability with α-3 configuration.

### 5.4 A3C vs GAE

The A3C algorithm is suitable for optimisation problems in which the dynamics of achieving the optimum are unknown. Using an actor-critic approach and network architecture, A3C explores the state-space and reduces the action space to the most feasible actions entailing best reward. Similarly, GAE ($\lambda$) simply uses $\lambda$-return to estimate the advantage function and thus allows us to estimate the advantage and value functions in RL with easy control over bias-variance trade-off. Based on the results of the previous experiments, the $\alpha$-3 learning rate configuration is chosen with learning rates of $10^{-4}$ and $10^{-3}$ for the policy and value networks respectively. A single case of accelTime = 7s, top Speed = 100 m/s and range = 200 km is considered. In Fig. 6(a) for training and (b) for evaluation, A3C and GAE ($\boldsymbol{\gamma} = 0.99$, $\lambda = 0.5$) algorithms are compared. There is little difference at the final stage of learning process between the two algorithms, but GAE is more stable throughout the training process.

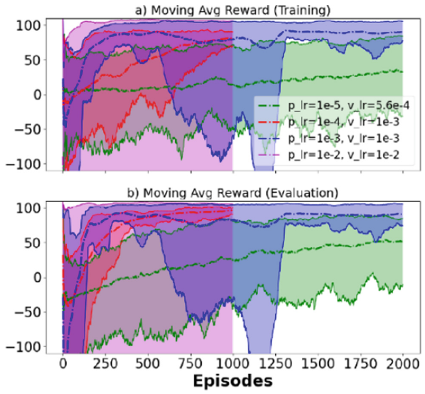



**Fig. 5.** Effect of varying the learning rate on the reinforcement machine learning framework

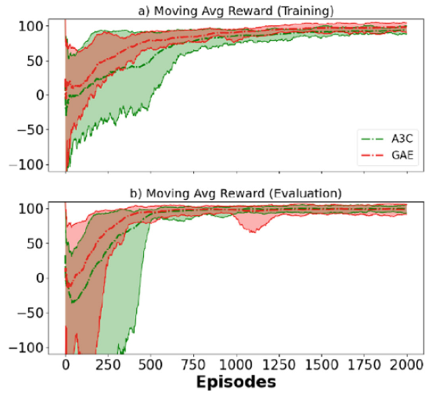



**Fig. 6.** Comparison between A3C and GAE on training/evaluation convergence

## 6 Conclusion

EV industry is growing at enormous rate of 45% per annum [25], but practical challenges remain to cope with optimising the wide variety of parameters in the practical design of EV meeting certain requirements e.g., top speed, acceleration. The optimisation of a large number of multi-modal discrete and continuous variable is a complex challenge that requires a pragmatic optimisation framework [26]. This paper presents a RL framework integrating a vast number of input parameters and constraints to identify feasible designs. This tuned framework has been tested on accurate powertrain simulation models by EV component manufacturer YASA and demonstrated that it can be used to dictate convergence towards certain feasible parameter regions in the design of EV for specific applications. To the authors' best knowledge, this is the first attempt to apply a RL framework on such a complex mixture of wide ranging continuous and discrete variables in the electric vehicle powertrain optimisation domain.

**Acknowledgements.** The authors would like to acknowledge the ASTUTE 2020 (Advanced Sustainable Manufacturing Technologies) operation supporting manufacturing companies across Wales, which has been part-funded by the European Regional Development Fund through the Welsh Government and the participating Higher Education Institutions.

## References

1. Aijaz, I., Ahmad, A.: Electric vehicles for environmental sustainability. In: Agarwal, P., Mittal, M., Ahmed, J., Idrees, S.M. (eds.) Smart Technologies for Energy and Environmental Sustainability. GET, pp. 131–145. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-80702-3_8
2. Lynette, L.W., Cheah, W.T.: Cars on a diet : the material and energy impacts of passenger vehicle weight reduction in the U.S. https://dspace.mit.edu/handle/1721.1/62760?show=full. Accessed 8 July 2022
3. Kuklinska, K., Wolska, L., Namiesnik, J.: Air quality policy in the U.S. and the EU – a review. Atmos. Pollut. Res. **6**(1), 129–137 (2015). https://doi.org/10.5094/APR.2015.015
4. Yang, L., Gobbi, M., Mastinu, G., Previati, G., Ballo, F.: Multi-disciplinary optimisation of road vehicle chassis subsystems. Energies **15**(6), 2172 (2022). https://doi.org/10.3390/EN15062172
5. Sierzchula, W., Bakker, S., Maat, K., van Wee, B.: The influence of financial incentives and other socio-economic factors on electric vehicle adoption. Energy Policy **68**, 183–194 (2014). https://doi.org/10.1016/J.ENPOL.2014.01.043
6. Akehurst, S.: An investigation into the loss mechanisms associated with a pushing metal V-belt continuously variable transmission, Ann Arbor, (2001). https://www.proquest.com/dissertations-theses/investigation-into-loss-mechanisms-associated/docview/1477294801/se-2?accountid=14680
7. Gokasan, M., Bogosyan, S., Goering, D.J.: Sliding mode based powertrain control for efficiency improvement in series hybrid-electric vehicles. IEEE Trans. Power Electron. **21**(3), 779–790 (2006)
8. Bilgin, B., et al.: Making the case for electrified transportation. IEEE Trans. Transp. Electrification **1**(1), 4–17 (2015)
9. Tran, M.K., Akinsanya, M., Panchal, S., Fraser, R., Fowler, M.: Design of a hybrid electric vehicle powertrain for performance optimization considering various powertrain components and configurations. Vehicles **3**(1), 20–32 (2020)
10. Miri, I., Fotouhi, A., Ewin, N.: Electric vehicle energy consumption modelling and estimation—a case study. Int. J. Energy Res. **45**(1), 501–520 (2021)
11. Wang, L., Zhao, X., Liu, L., Wang, R.: Battery pack topology structure on state-of-charge estimation accuracy in electric vehicles. Electrochim Acta **219**, 711–720 (2016)
12. Song, X., Wen, X., Zhao, F., Liu, J., Xu, L.: A control and drive system for permanent magnetic dual mechanical port electric machine used in hybrid electric vehicles. In: 2009 International Conference on Electrical Machines and Systems, pp. 1–4 (2009)
13. Javied, A., Rajasegarar, S., Arshad, K., Moessner, K.: A statistical moment deviation approach to identify outliers in collaborative spectrum sensing for cognitive radio, **1**(1), 4-6 (2017)
14. Kivekäs, K., Lajunen, A., Vepsäläinen, J., Tammi, K.: City bus powertrain comparison: driving cycle variation and passenger load sensitivity analysis. Energies (Basel) **11**(7), 1755 (2018)
15. Pathak, A., Sethuraman, G., Krapf, S., Ongel, A., Lienkamp, M.: Exploration of optimal powertrain design using realistic load profiles. World Electr. Veh. J. **10**(3), 56 (2019)
16. Torquato, M.F., et al.: Cascade optimisation of battery electric vehicle powertrains. Procedia Comput. Sci. **192**, 592–601 (2021). https://doi.org/10.1016/j.procs.2021.08.061

17. Li, Y., Zhu, B., Zhang, N., Peng, H., Chen, Y.: Parameters optimization of two-speed powertrain of electric vehicle based on genetic algorithm. Adv. Mech. Eng. **12**(1), 1687814020901652 (2020)
18. König, A., Nicoletti, L., Schröder, D., Wolff, S., Waclaw, A., Lienkamp, M.: An overview of parameter and cost for battery electric vehicles, World Electr. Veh. J. **12**(1) (2021). https://doi.org/10.3390/WEVJ12010021
19. Javied, A.: Application partitioning and offloading in mobile cloud computing, University of Surrey (2017)
20. Ganesh, A.H., Xu, B.: A review of reinforcement learning based energy management systems for electrified powertrains: progress, challenge, and potential solution. Renew. Sustain. Energy Rev. **154**, 111833 (2022)
21. Chen, I.M., Zhao, C., Chan, C.Y.: A deep reinforcement learning-based approach to intelligent powertrain control for automated vehicles. In: 2019 IEEE ITSC, pp. 2620–2625 (2019)
22. Hu, X., Liu, T., Qi, X., Barth, M.: Reinforcement learning for hybrid and plug-in hybrid electric vehicle energy management: recent advances and prospects. IEEE Ind. Electron. Mag. **13**(3), 16–25 (2019)
23. Paszke, A., et al.: PyTorch: an imperative style, high-performance deep learning library. In: Advances in Neural Information Processing Systems 32. Curran Associates, Inc., pp. 8024–8035 (2019). http://papers.neurips.cc/paper/9015-pytorch-an-imperative-style-high-performance-deep-learning-library.pdf
24. Li, X., Chen, S., Hu, X., Yang, J.: Understanding the disharmony between dropout and batch normalization by variance shift. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pp. 2682-2690 (2018)
25. Yong, J.Y., Ramachandaramurthy, V.K., Tan, K.M., Mithulananthan, N.: A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. Renew. Sustain. Energy Rev. **49**, 365–385 (2015)
26. Coit, D.W., Zio, E.: The evolution of system reliability optimization. Reliab. Eng. Syst. Saf. **192**, 106259 (2019)

# Digital, Scalable Manufacturing - A Sustainable Production Scenario Using Collaborative Robotics and Additive Manufacturing

Tobias Mueller[1,2](✉), Andreas Schmidt[1], Steffen Scholz[1,2], and Veit Hagenmeyer[1]

[1] Karlsruhe Institute of Technology, Karlsruhe, Germany
tobias.mueller2@kit.edu

[2] Karlsruhe Nano Micro Facility (KNMFi), Eggenstein-Leopoldshafen, Germany

**Abstract.** Industry 4.0 has become a well-known production paradigm over the last decade. It represents innovation and creativity in research and industry but also aims at including digital innovation into the manufacturing area. Robotics, automation and handling of large data sets are key to fully exploit the potential of Industry 4.0. Within this work, a novel production approach combining collaborative robotics, additive manufacturing and a state-of-the-art control and data acquisition approach is conceptualized and implemented. At Karlsruhe Institute of Technology (KIT), Germany, an exemplary setup is implemented based on the use of four identical robotic systems, fused filament fabrication and databases to capture data from sensors and machinery in real-time. The setup will show the capabilities of state-of-the art flexible, scalable manufacturing concept in order to release the full potential of Industry 4.0 and enhance the flexibility and sustainability of current and future value chains.

**Keywords:** Sustainable production · Industry 4.0 · Collaborative robotics · Additive manufacturing

## 1 Introduction

Over the past decades, production has evolved from a mere application of serial production that allows for the increase of production volumes and cost reduction [1, 2]. The application of robots allowed for the automation of repetitive tasks, which offers a variety of advantages like the reduction of throughput time, quality improvements or the increase of workers' health by using robots for unhealthy or risky tasks [3].

Within the past years, manufacturing scenarios are facing mainly two new challenges: 1) the demand for higher flexibility due to shortened product life cycles and customization trends and 2) the need to create more sustainable production approaches enabling a better use of resources [4, 5].

Several approaches can be used to overcome these challenges, ranging from creating a robust facility layout enabling a rearrangement of production modules [6, 7] or the implementation of different manufacturing techniques based on the properties of the final product [8] to the implementation of robotics and human-robot collaboration. Concepts


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 262–271, 2023.
https://doi.org/10.1007/978-981-19-9205-6_25

like these can be a basis for a more flexible production approach in certain areas, like for example the shoe industry [9]. Additionally, uprising manufacturing techniques like additive manufacturing allow for a sustainable use of resources in comparison to traditional subtractive techniques [10], while a sophisticated process control can minimize the number of defective parts produced by detecting changes in processing parameters and adapting in real-time [11].

While all of these approaches have been demonstrated on its own and even partly transferred into actual production, the combination of several or even all of these paradigms is still an ongoing research topic. At the Karlsruhe Institute of Technology (KIT), Germany, a production concept is envisaged that combines a flexible shopfloor layout planning with easy reorganization of robotic manufacturing cells, collaborative robotics that allow for more precise handling and assembly, process control via a variety of implemented sensors as well as the acquisition, processing and management of data sets from machinery, robots and sensors [12, 13]. This so-called "Wertstromkinematik" (WSK) vision [14] is therefore one of the first approaches that enables to incorporate a variety of the above-mentioned technologies that will help to overcome the future challenges and implement a truly sustainable and flexible manufacturing scenario.

Within this work, a production setup will be implemented that demonstrates the vision of a flexible, scalable manufacturing approach based on the integration of collaborative robots, additive manufacturing and a real-time-control approach that has been partly developed within the WSK project. In the following sections, the concept of WSK will be presented in more detail, the demonstration scenario will be described with all its individual components along with the current status and an outlook will be given on the next steps involving this particular research topic at KIT.

## 2 Innovative Concept for Scalable and Sustainable Manufacturing

As the demand for customization or even personalization of consumer products increases, the manufacturing industry is looking for new production concepts allowing for more flexibility in setting up a manufacturing process chain. As a second aspect, green production and sustainability are also a main driving force urging the implementation of new approaches.

With the WSK vision, a consortium of different institutes of the KIT and the Hochschule Karlsruhe are aiming at tackling these issues by developing a production scheme based on the application of identical robots, that interact with each other to fulfill even the most challenging manufacturing tasks. The interaction allows for expanding the use of robots apart from mere handling tasks to actual complex production and assembly steps while increasing the forces and precision applicable to those processes. The goal is to enable the replacement of specialized, expensive machines that are sometimes only used for one specific task, helping to slim down the overall process chain and facilitate the switch between different products even more, which poses a huge benefit for production companies.

Figure 1 shows the basic principle of the WSK concept. The shopfloor is divided into a grid of docking points that are designed to connect to the individual robot units used for each manufacturing scenario. The docking points provide all connections (power, network, sensor connections…) that are necessary to power and control the individual robots as well as gather data from the process via implemented sensors, preferably in real-time.

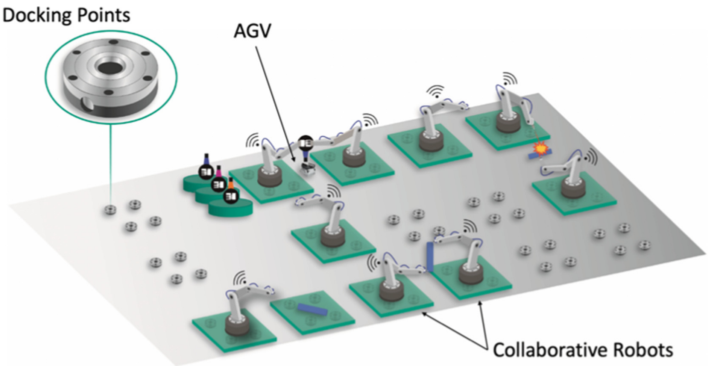



**Fig. 1.** Vision of the Wertstromkinematik concept [12]

The robotic cells are not only designed to carry out rather simple handling tasks, but should also be able to collaborate closely in order to perform complex and challenging production tasks that require the application of high force or high precision. This is not feasible with today's industrial robots. However, this problem can be resolved by coupling of two or multiple robotic systems (Fig. 2), that interact according to a preliminary trajectory planning and perform complex assembly or manufacturing steps.

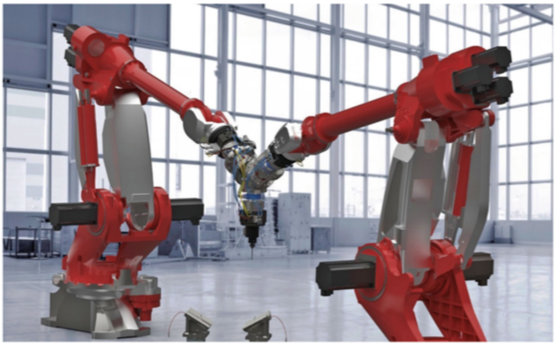


**Fig. 2.** Visualization of coupled industrial robots (Comau NJ290 3.0) for performing complex manufacturing tasks [12]

In order to gather information on the performed processes, the robots are equipped with additional sensors that are able to provide data on the state of the production cell (occupied, unoccupied), physical conditions while a procedure is carried out (acting forces, acceleration…) and the quality of the product currently being processed. This data is collected and analyzed either in real-time or after a certain production step has been carried out. With this data basis a digital process chain can be generated, allowing for the planning of upcoming production scenarios by selecting the right combination of tools, adapting production parameters from previous but similar process chains and also to optimize already existing processes by investigating the data closely. An overview of the digital architecture of this framework is shown in Fig. 3.

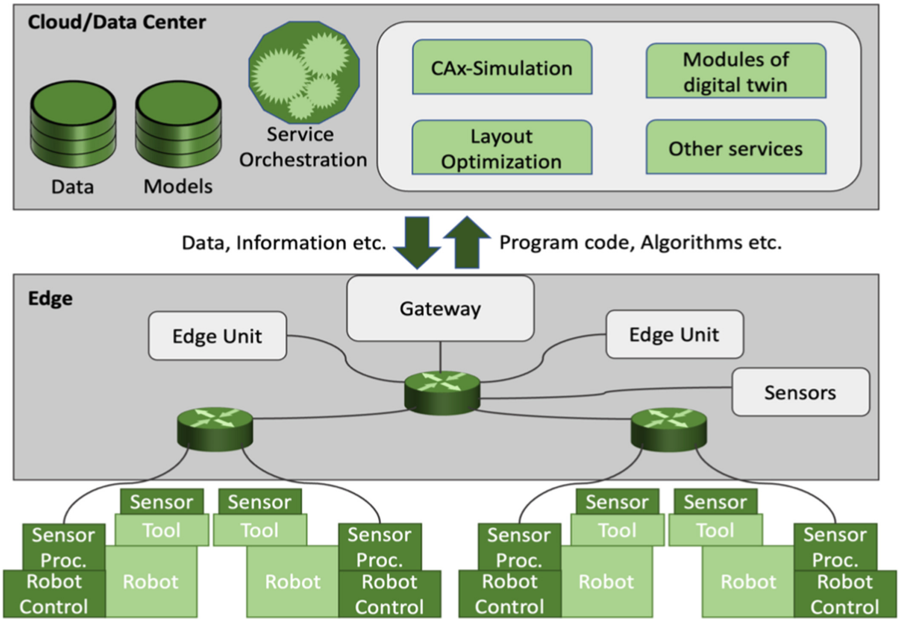



**Fig. 3.** Digital framework architecture for collection, preparation and storage of process-relevant data

A second use of the gathered information is a real-time optimization of the production. By identifying variances between the planned program and the actual performance, the processing parameters can be adapted accordingly allowing to react on changing conditions that may occur due to unexpected behavior, collisions, tool wear or slight variances in material behavior.

Finally, the digital framework of the WSK also relies on a simulation tool that is capable of building and simulating a wide variety of production scenarios. Based on the data and experience from previous production runs, information on upcoming products (CAD-files, material properties, final part properties) the setup of the robotic systems, toolsets as well as an initial trajectory planning can be performed and tested virtually. This concept allows to test different scenarios prior to installation on the actual shop floor and thereby reduces the time and costs spent on finding the right setup and facilitates a first-time-right approach.

Another aspect covered in the project is how such a change in the production paradigm has to be seen in a social aspect as well. By changing the interaction between humans and machines, such a concept may also have an influence in how these technologies are received by the workforce and the general public. Therefore, the social impact is taken account for by considering political, societal and regulatory framework conditions. In addition to the inclusion of relevant scientific analyses, handouts and reports on the broader range of topics of digitization in the world of work, artificial intelligence or data security, specific questions of the WSK will also be explored.

It is obvious that such a holistic concept does involve expertise from a variety of research fields including traditional mechanical engineering, information technology, robotics, process control as well as a social and regulatory point of view.

## 3 Demonstration Scenario

### 3.1 Hardware Setup

Based on the concept of WSK individual scenarios can be realized, each aiming at a different niche in manufacturing. One of these cases is the implementation of a large number of production machines/elements in the process chain and using the robots to carry out a variety of tasks to fabricate a complex final product. To visualize and investigate such a scenario, a demonstrator has been installed at the Institute for Automation and Applied Informatics (IAI) of KIT combining multiple 3D printers, robots and a sophisticated control and data acquisition system. The general idea of this approach is to showcase the possibilities that a production process can provide in terms of scalability and sustainability when combining a highly flexible manufacturing method such as additive manufacturing with state-of-the-art automation and information technologies.

The demonstrator consists of three different elements:

- Hardware for the production itself (3D printers, robots, tools)
- Hardware for data acquisition, processing and management
- Software for controlling all elements, data acquisition, processing and management

In order to fabricate parts and establish a production scenario capable of high flexibility in terms of materials, geometries and batch volume, additive manufacturing is an obvious choice nowadays, except for actual mass production. Therefore, within this scenario the production step is carried out by a large number of fused filament fabrication printers (Prusa i3 MK3S). While these machines can print with a large variety of polymer materials and with high resolution, more complex products require post-processing steps of the printed parts. These can be carried out by the collaborative robotic systems integrated in the demonstration setup. A total of four Franka Emika Panda robots are positioned in a way that they can remove parts from the printing platform after the prints are finished and they can perform additional task the manufacturing scenario might require such as removal of support material, assembly of individual parts from different printers or handling & assembly of proprietary components to be included in the final part. In order to fulfill these requirements, a production setup has been developed and installed where four collaborative robots can work together with a total of 16 printers, as shown in Fig. 4.

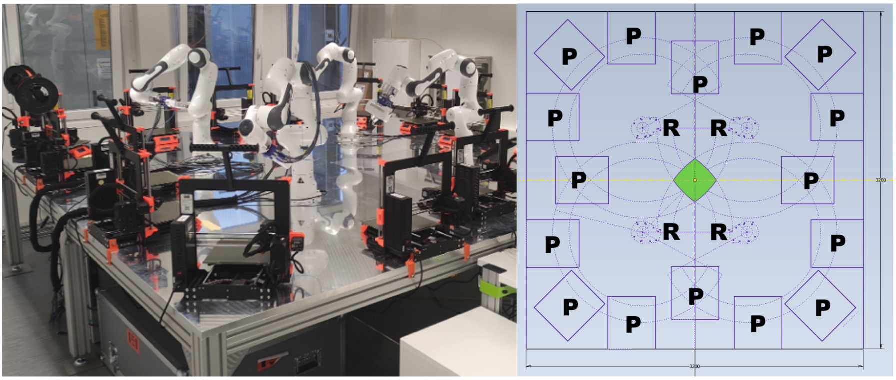



**Fig. 4.** Demonstrator for flexible, scalable manufacturing; real-life setup (left), scheme of positioned participants (robots (R), printers (P); right)

The setup allows all robots to access the printers' platform, but also includes areas for interaction to carry out precise, collaborative tasks like removing support material or assembly and inspection steps.

In order to coordinate such a high number of participants in a single production process, the control and information management is of high importance. To gather data on the actual state of the setup, the demonstrator is equipped with a number of sensors and data acquisition systems that can deliver data on high frequency. This specific demonstrator includes:

- Force and Torque sensors in all joints of the robotic systems to track changes while moving along the trajectory
- Readout capabilities for the state of the 3D printers (On/Off, % of completion, error tracking)
- High-frequency Force-Torque measurement at the end-effector coupling to determine forces acting while parts are gripped
- Acceleration sensors on the end effector to measure g-forces while movement
- Energy monitoring for all printers and robots to identify possible energy saving scenarios

In order to gather these datasets at a high rate, the acquisition systems have to be capable of high frequency readout and processing as well as to allow flexible modeling of the different setups of the hardware. The components were specifically chosen to allow for a high data readout rate.

### 3.2 Data Management

For the setup described above, there are specific requirements for the data management system due to the high flexibility and interaction of the components involved. Concrete, the following points must be considered in detail:

**Metainformation:** Due to the high flexibility in the setup of the robots and printers, a suitable description (modeling) of the current production scenario must be possible, so that information about the available sensors and actuators is possible at runtime. This includes the assignment of the sensors to the available robots and their positioning as well as the data sinks assigned to the sensors. Furthermore, access to the sensors must be possible at runtime. This includes both the activation/deactivation of sensors, the definition of the sampling rate as well as the query and modification of the data sinks.

**Attributation:** Furthermore, the system must be able to save the process parameters used for individual production or test runs. Such process parameters include, for example in case of the additive manufacturing scenario, the G-code used to control the printers and the trajectories or gripping force of the robots. This feature ensures the reproducibility of the production/test runs.

**Velocity:** During a production/test run, a large number of sometimes high-frequency sensor values are generated, which must be stored in a suitable manner so that they can be analyzed later. The data rate and the necessary precision of the time stamps are critical requirements here, especially in distributed environments.

**Data Interfaces:** Following the production/test runs, complex evaluations of the accumulated data may have to be performed. This requires that all accumulated data must be determined and can be offered to internal or external applications (e.g. AI) via a suitable interface.

Critical for the selection of a suitable database system (or several different systems) are in particular the following points:

**Highly Precise Time Stamps:** This requires the use of a local NTP-server that provides the components involved with precise time stamps in the sub-millisecond range. It is also important to assign the timestamps to a measurement as quickly as possible and not only upon entering them into the database. Depending on the technology used, this can already be done at the control pc or even when the sensor values are recorded directly at the sensor. This mechanism makes it possible to send sensor values together with their meta information and time stamps to the database in batchmode, which massively increases the throughput of the measured values compared to having to write each measured value individually to the database.

Due to the required high sampling rate and the resulting data volumes, a time series database is the obvious choice here, as it can handle a much higher write load compared to transactional systems. The loss of individual data records can be neglected in this scenario.

**Flexible Modeling Capabilities:** TO implement the above-mentioned points "Metainformation" and "Attributation", the database system must have flexible modeling and query capabilities. However, transactional support is also necessary here, since it is essential for the database system to be in a consistent state and the loss of individual instructions can't be tolerated. However, the time requirements for this system are not particularly high. For reasons of flexibility, a schema-free database, e.g., a document-store, is a good choice here. However, these NOSQL systems usually have limited transactional capabilities whose granularity is limited to one document at a time. However, since n:m relationships that extend over several documents are predominant in the scenario presented here, this option is ruled out.

Therefore, a relational database management system is the obvious choice, which provides fixed schemas, but can provide the flexibility required above through suitable modeling. An alternative might be a property graph database system with transactional support, such as Neo4j [15].

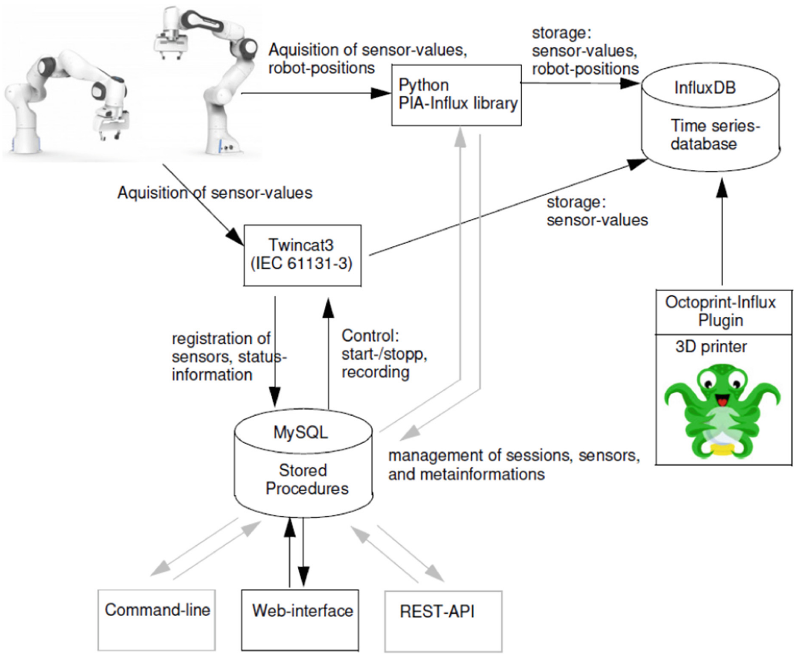



**Fig. 5.** Implemented data management architecture

The overall architecture of our current system is shown in Fig. 5. Due to the different interfaces of the sensors, we currently have two types of data acquisition units. On the one hand, we use the TwinCAT [16] automotive software from Beckhoff. This runs on an industrial pc with windows specially adapted for real-time applications. This software runs on an industrial PC with windows specially adapted for real-time applications. The data acquisition rate is up to 1000 Hz with the currently used sensors, but can be further increased by using special sensors through oversampling. The sensor data values collected via the TwinCAT system are either written directly into the InfluxDB or via an intermediate step into a local file and from there into the Influx database using the telegraph [17] plugin. Values from sensors that are not connected to the TwinCAT system are written to the Influx database using a dedicated Python library. This library is also used to record the position of the grippers of the robots. As a second central storage unit, we use a relational MySQL database. This database is responsible for managing the sessions and sensors. All data collection takes place in the context of sessions. Via the two acquisition units (TwinCAT and the python library), the available sensors register themselves with the MySQL database. Through this interface, the acquisition of sensor values can also be started and stopped. This is done by assigning appropriate values for the concrete sensor data set. Setting these values in turn is done through various interfaces, such as a web interface, a REST API or the command line.

In comparison to conventional production setups, the combination of the presented hardware and state-of-the-art data management and control system results in several advantages. It enables a high degree of flexibility in the production step up to even one-off products due to the nature of AM. Sustainability is also a key advantage, as the system can be tuned in real-time, avoiding process-related failures and waste of energy, materials and time. Finally, scalability is emphasized as multiple, similar production cells can be established on the shopfloor easily, allowing for shirt ramp-up times as well as throttling depending on the current demand for the manufactured parts.

## 4 Conclusion and Outlook

The production concept discussed in this paper has the potential to permanently change the future of production technology. As a visionary production system, it takes into account the characteristics of innovative, sustainable production. The use of modular robotics systems, capable of performing variety of tasks, makes specialized machinery obsolete. A sophisticated process control architecture on different levels reduces the number of errors during the manufacturing step, aiming for a zero-defect result. Additive manufacturing as part of the modular process chain helps to minimize material consumption and increases the flexibility.

However, in order to successfully implement the vision described here, a close exchange between different scientific fields and a consistent consideration of common interfaces is required.

**Acknowledgement.** This work was carried out with the support of the KIT Future Fields measure, the Karlsruhe Nano MicroFacility (KNMFi, www.knmf.kit.edu) a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu) and under the Helmholtz Research Programme MSE (Materials, Systems, Engineering) at KIT.

## References

1. Alexopoulos, K., Makris, S., Chryssolouris, G.: Production. CIRP Encyclopedia of Production Engineering, pp. 1–5, Springer, Berlin, Heidelberg (2018)
2. Chryssolouris, G.: Manufacturing Systems: Theory and Practice. Springer, Berlin (2006)
3. Lien, T.K.: Robot in the international academy for production engineering. In: Laperrière L, Reinhart. G (eds.) CIRP Encyclopedia of Production Engineering, pp. 1068–1076, Springer, Berlin Heidelberg (2014)
4. Jamwal, A., Agrawal, R., Sharma, M., Giallanza, A.: Industry 4.0 technologies for manufacturing sustainability: a systematic review and future research directions. Appl. Sci. **11**(12), 5725 (2021)https://doi.org/10.3390/app11125725

5. Tseng, M.-L. et al: Sustainable industrial and operation engineering trends and challenges toward industry 4.0: a data driven analysis. J. Ind. Product. Eng. **38**(8), pp. 581–598, (2021). https://doi.org/10.1080/21681015.2021.1950227
6. Pourvaziri, H., et al.: Robust facility layout design for flexible manufacturing: a doe-based heuristic. Int. J. Prod. Res. (2021). https://doi.org/10.1080/00207543.2021.1967500
7. Pérez-Gosende, P., Mula, J., Díaz-Madroñero, M.: Facility layout planning. an extended literature review. Int. J. Prod. Res. **59**(12), 3777–3816 (2021). https://doi.org/10.1080/00207543.2021.1897176
8. Scholz, S. et al: SMARTLAM-a modular, flexible, scalable, and reconfigurable system for manufacturing of microsystems. In: INTELLI 2015, p. 154ff (2015)
9. Zhang, S., Li, S., Wang, H., Li, X.: An intelligent manufacturing cell based on human–robot collaboration of frequent task learning for flexible manufacturing. Int. J. Adv. Manufact. Technol. 1–16 (2022). https://doi.org/10.1007/s00170-022-09005-6
10. Peng, T., et al.: Sustainability of additive manufacturing: an overview on its energy demand and environmental impact. Addit. Manufact. **21**, 694–704, (2018) ISSN 2214–8604, https://doi.org/10.1016/j.addma.2018.04.022
11. Fu, Y., Downey, A., Yuan, L., Pratt, A., Balogun, Y.: In situ monitoring for fused filament fabrication process: a review. Addit. Manufact. **38** (2021). ISSN 2214–8604
12. Mühlbeier, E., Oexle, F., Gönnheimer, P., Fleischer, J.: Wertstromkinematik – Produktionssysteme neu gedacht: Interdisziplinäres Forscherteam arbeitet an der Produktionstechnik der Zukunft (Teil 1). Zeitschrift für wirtschaftlichen Fabrikbetrieb **116**(11), 847–851 (2021). https://doi.org/10.1515/zwf-2021-0179
13. Kimmig, A., Schöck, M., Mühlbeier, E., Oexle, F., Fleischer, J.: Wertstromkinematik – Produktionssysteme neu gedacht: Interdisziplinäres Forscherteam arbeitet an der Produktionstechnik der Zukunft (Teil 2). Zeitschrift für wirtschaftlichen Fabrikbetrieb **116**(12), 935–939 (2021). https://doi.org/10.1515/zwf-2021-0207
14. Wertstromkinematik Homepage. http://wertstromkinematik.de/. Accessed 27 Apr 2022
15. Robinson, I., Webber, J., Eifrem, E.: Graph Databases. Beijing, O'Reilly (2015)
16. Beckhoff Homepage. https://www.beckhoff.com/. accessed 03 May 2022
17. InFlux Homepage. https://www.influxdata.com/time-series-platform/telegraf/. Accessed 02 May 2022

# Development of a Novel Laser Polishing Strategy for Additively Manufactured AlSi10Mg Alloy Parts

Ben Mason[1](✉), Michael Ryan[1], Rossi Setchi[1], Abhishek Kundu[1], Wayne Nishio Ayre[2], and Debajyoti Bhaduri[1]

[1] School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
MasonB4@cardiff.ac.uk
[2] School of Dentistry, Cardiff University, Cardiff CF14 4XY, UK

**Abstract.** Post-processing of additively manufactured (AM) aluminium alloy parts via laser polishing (LP) is particularly challenging due to the materials' high thermal conductivity, diffusivity, and reflectivity. Here, a novel multi-step laser polishing strategy, by combining laser ablation and smoothing steps, is developed that effectively reduces the surface roughness of AM AlSi10Mg parts. The minimum average roughness (Sa) and 10-point height (S10z) are achieved as 1.81 μm and 23.7 μm, representing maximum reductions of 94.1% and 89.8%, respectively, from the as-built AM surfaces (initial Sa 8–28 μm). A strong relationship has been observed between the initial surface roughness and the achievable roughness reduction. Regarding the other surface integrity factors, sub-surface microhardness (between 10–40 μm) after LP increases up to 182 $HV_{0.01}$, compared to the bulk hardness (105 $HV_{0.01}$) measured ~60 μm below the surface. Clear evidence of material's flow within the surface asperities during the LP steps is observed from the cross-sectional microstructures. Further study will involve in-depth analysis of materials' compositions within the LP-processed layers.

**Keywords:** Laser polishing · Additive manufacturing · AlSi10Mg alloy

## 1 Introduction

Additive Manufacturing (AM) offers immense benefits for design and manufacturing engineers, from the unparalleled geometric freedom afforded to unique material properties and potential for producing functionally-graded parts. Despite the reported advantages of AM technology over the conventional subtractive manufacturing methods, AM parts, especially metal parts, suffer from substandard surface roughness, requiring extensive post-processing before functional use [1]. There are a number of techniques available to modify the surface roughness of components, such as mechanical milling, grinding, electro-chemical polishing and so on, however these methods either suffer from reduced geometric freedom (in the case of milling) or cause environmental concerns (e.g., electrochemical polishing).


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 272–282, 2023.
https://doi.org/10.1007/978-981-19-9205-6_26

Laser Polishing (LP) is a promising alternative for the surface modification of AM parts. LP is a flexible, non-contact and automated method, only requiring line-of-sight between the optics and the surfaces to be processed, retaining much of the geometric freedom afforded by AM. LP also does not require any chemicals, and with a very low material removal the environmental concerns are also minimised.

## 2 Literature Review

### 2.1 AM Surfaces

It is well known that AM parts have much higher surface roughness values compared to the conventionally manufactured parts. A typical AM surface can have roughness values in the region of ~5–15 μm Ra, compared to milled surfaces, typically with ~0.5–6 μm Ra [2]. The high surface roughness of AM parts is detrimental to their functional properties such as tribological characteristics and fatigue resistance, as well as for their aesthetic appearance [3, 4]. These AM surfaces are dominated by tall peaks, deep valleys, adhered particles, and other surface contamination. While research has been undertaken to reduce the roughness by the AM parameters' optimisation [5, 6] the process is inherently limited in this regard due to the nature of the feedstocks limiting the possible resolutions and thus excess powder adhesion is common. Therefore, it is often necessary to post-process AM parts to reduce the surface roughness to an acceptable level.

### 2.2 Laser Polishing

Laser Polishing (LP), or more generally laser surface remelting, is the process of exposing a surface to laser irradiation to reduce the surface roughness. This occurs through melting of the surface material, which then flows by the effects of surface tension and capillary forces from high points (asperities) to low points (valleys). Due to the very high thermal gradients present in and around the melt pool ($>10^3$ K/mm [7]) the molten flow is highly turbulent, leaving a certain degree of residual roughness after each pass. When using a pulsed wave (PW) laser source, the residual surface texture also incorporates evidence of individual melt pools from the repeated melting and solidification as the bean traverses the surface.

With an excess energy input, a portion of the molten material vaporises and can be removed by extraction systems. This is known as ablation. Ablation results in a degree of material loss (~10 μm/pass) however at a much lower rate than would be expected by traditional machining processes (e.g., for milling, material loss is $>500$ μm/pass).

Both laser remelting and ablation processes are shown schematically in Fig. 1. One advantage of laser post-processing is the capability to incorporate surface functionalisation, such as adding textures to improve tribological performance [8] or corrosion resistance [9].

### 2.3 Laser Polishing of Aluminium Alloy Parts

Laser polishing has been implemented to post-process a varied range of metallic AM materials, such as stainless steel, titanium and nickel alloys over the past 20 years [10],

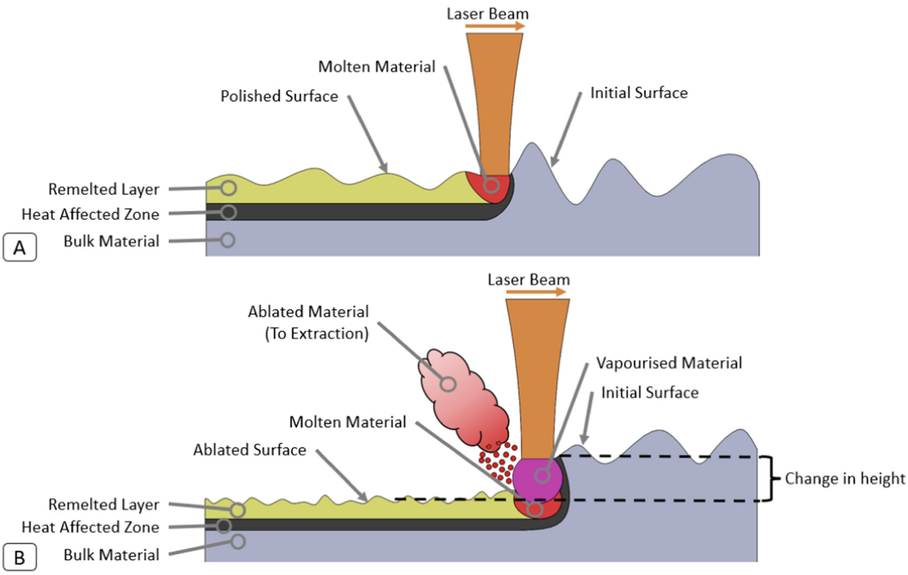



**Fig. 1.** Schematics of the (A) Laser polishing and (B) Laser ablation processes.

however to a much-limited extent on aluminium-based alloys. This is because LP of aluminium alloy parts exhibits a particular challenge as the technology can be executed within a very narrow processing window. The high thermal conductivity (130–190 W/mK [11]) and high reflectance (>85% [12]) of Al alloys necessitate high energy inputs to heat the material, while the low melting point (~580 °C) can result in overheating of the parts. Furthermore, aluminium readily oxidises in air, and this oxide layer requires even more energy to melt.

So far, research into LP of AM aluminium has utilised both continuous wave [13], and nanosecond pulsed [14] laser systems. Despite the reported improvement in surface roughness following LP (~95%) it is difficult to draw conclusive remarks on the actual roughness reduction as either discrete LP locations were analysed for roughness measurement [13, 15] or different roughness filters were used for the polished and unpolished surfaces (0.8 mm and 0.25 mm respectively) [1, 16]. Since the quality of the AM surfaces vary greatly, it is essential to measure the same area before and after any surface treatment, where possible, and identical data processing operations applied.

The aim of this research is to develop a novel LP strategy that can effectively reduce the roughness of AM AlSi10Mg parts' surfaces. A multi-stage process is presented to combine ablation of large surface asperities, with remelting to remove smaller-scale features from the surface.

# 3 Methodology

## 3.1 Manufacture of the AM Specimens

The AM specimens were fabricated on a Renishaw AM250 laser-based powder bed fusion (L-PBF) system, using gas-atomised AlSi10Mg powder, also sourced from Renishaw plc. [11]. The manufacturing settings are recommended by the machine manufacturer for this particular Al alloy and are provided in Table 1, using the "meander" scan strategy. The samples measured 50 mm × 40 mm × 3 mm, with the 50 × 40 $mm^2$ surface built vertically onto an aluminium baseplate.

**Table 1.** AM samples' manufacturing settings.

| AM parameters | Values |
|---|---|
| Laser power | 200 W |
| Hatch spacing | 100 μm |
| Point distance | 80 μm |
| Exposure time | 140 μs |
| Oxygen content | <500 ppm |

## 3.2 Laser Polishing

The 50 × 40 $mm^2$ surfaces (built vertically) were chosen for the laser polishing trials due to their higher surface roughnesses compared to the horizontally built surfaces. LP tests were conducted using a DMG Lasertec 40 laser milling centre, equipped with an SPI Lasers G3.1 laser source, the specifications of which are given in Table 2.

**Table 2.** Laser specifications for SPI G3.1 module.

| Laser machine specification | Value |
|---|---|
| Maximum average power | 20 W |
| Laser source | Yb-doped fiber laser |
| Focal spot diameter | 32 μm |
| Beam quality | $M^2 \approx 1.2$ |
| Emission wavelength | 1064 nm |
| Pulse frequency | ≤290 kHz |
| Pulse duration | 15–220 ns (pre-set) |

Two previous pieces of research were formative in the development of the LP methodology in the current research. The first by Bhaduri et al. [14], wherein the roughness reduction via a given LP strategy was improved by 80–88% when the samples were polished after placing them on a thermally insulating ceramic baseplate. It was surmised that the insulating baseplate reduced the conductive heat losses from the samples, reducing the cooling rates and in turn allowing the melt pools more time to re-flow before solidification. The researchers measured the sub-surface temperatures to be ~30% higher when using the baseplate compared to that recorded without the baseplate. Based on this, all trials in the present study were conducted with a thermally insulating ceramic baseplate between the samples and the laser machine's X-Y stage (made of stainless steel).

The second piece of work was by Petkov et al. [17] who proposed a multi-step strategy for LP of AM titanium alloy parts, comprising of steps designed to ablate the very tall peaks of the surfaces, followed by steps to remelt and smooth the surfaces. Previous unpublished work at Cardiff University developed an effective laser ablation strategy for AM AlSi10Mg samples, with laser pulse durations ($T_e$) of 15 ns, a pulse frequency ($f$) of 290 kHz, and fluence ($F$) of 14 J/cm$^2$.

Furthermore, in the work by Bhaduri et al. [14], the greatest smoothing effect for AM AlSi10Mg parts (~88% reduction in Sa after LP from the as-built surface) was found to be achieved with $F = 12$ J/cm$^2$, with pulse overlaps of 97% in both the X and Y directions. This was obtained using $T_e = 220$ ns and $f = 100$ kHz.

Based on these, it was determined a multi-step process combining ablation and smoothing steps would maximise the potential for smoothing AM aluminium surfaces. The main thrust of this work involved iterating the speeds ($v$) and hatch spacings ($h$) for each step to determine the optimal pulse overlaps in the range of 90–97% in X and Y directions. This resulted in scan speeds between 275 and 925 mm/s for the ablation steps, and 100 to 300 mm/s for the smoothing steps. The hatch spacings were between 1 and 3 μm for all steps. Once the optimal pulses' overlaps were determined, the number of laser scanning passes for each step was also iterated between 2 and 20, with an increment of 2 passes from the previous iteration. Iterating the number of passes was done holistically, ensuring changes to one step did not necessitate changes to any other steps in the strategy. Finally, the focal offset settings were chosen such that the optimal fluence and pulses' overlaps were maintained at the maximum average laser power.

Throughout all the trials, the effectiveness of LP was evaluated based on the surface roughness response. The roughness response was chosen as this is the most widely assessed surface integrity factor and also due to the shorter analysis time compared to that required to analyse other surface/material properties. Once the final LP strategy was determined, further evaluations were conducted with respect to other surface integrity responses such as porosity, microhardness, and microstructure.

### 3.3 Surface Integrity Evaluation of the LP Specimens

**Surface Roughness.** The surface roughness of the samples was measured using a Sensofar Smart optical profilometer using the Focus Variation (FV) technique. FV essentially works by imaging a surface with a very narrow depth of focus at various distances. In each image, different regions are in focus; an algorithm then determines at which height each pixel is in the greatest focus [18]. The resulting pixel heights can then be displayed as a surface map or processed to determine various surface roughness parameters. Four standard roughness parameters were used in this work, namely arithmetic mean height

(Sa), maximum peak height (Sp), maximum valley depth (Sv), and the ten-point height (S10z).

The surface roughness was initially measured on the unpolished surface and after each LP processing step to monitor the surface evolution through the strategy. Subsequently, only the initial and final surface roughnesses were measured. In all cases the surface measurements were post-processed using a 0.8 mm gaussian filter to isolate the roughness features.

**Sub-surface Porosity.** Once the final LP strategy was determined, a sample was laser polished according to the final strategy, sectioned, mounted, and mechanically polished using SiC papers, followed by diamond (6 and 3 μm) and silica (0.06 μm) suspensions.

Sub-surface porosity of the AM parts was estimated by direct observation on the cross-sections by using optical microscopy. A selection of the observed pores had the maximum dimensions measured, while the porosity was estimated using the ImageJ software to calculate the area coverage (%) from the surface to around 100 μm depth. Bulk porosity was estimated in a similar way, using optical micrographs from a central region.

**Microhardness.** Vickers microhardness measurements were conducted using a Mitutoyo MVK-G1 at a load of 0.01 kgf, and a dwell time of 10 s, in accordance with ASTM E92. Up to 50 μm depth below the LP surfaces, indents were spaced ~5 μm apart along the depth. Beyond this, the spacing was 10 μm to a final depth of 150 μm. Four indents were made at each depth at different locations. Indent diameters and depths below LP surfaces were measured using a Leica DM-LM optical microscope.

**Microstructure.** LP specimens were immersion etched in Keller's reagent (2.5% Nitric acid, 1.5% Hydrochloric acid, 1% Hydrofluoric acid) for 30 s to reveal the microstructure. Micrographs of the microstructure were then taken and inspected.

## 4 Results and Discussion

### 4.1 Surface Roughness

The optimum laser parameters of the developed LP strategy that rendered the minimum surface roughness values are listed in Table 3, while Fig. 2 displays how each LP step affected the roughness values with respect to the as-built surfaces. Figure 2 reveals that the first ablation step has the greatest influence on the Sa, Sp, and S10z values, while the final smoothing step causes the greatest reduction in Sv. Furthermore, only the Sp value is improved by the third step, clearly showing the ablation steps are effectively targeting surface asperities, while the smoothing step promotes material's filling in of the valleys. This exemplifies the benefit of the multi-step approach as the combination is far more effective than any one step in isolation when considering a range of roughness parameters.

Figure 3 shows surface height maps and optical images of the same surface region in the as built state (A) and after each LP processing step (B-E). It is evident from the

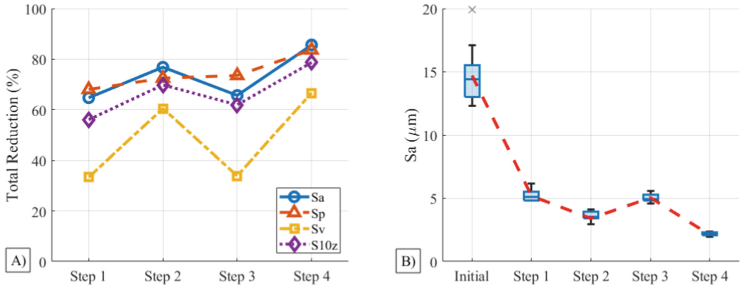



**Fig. 2.** (A) Total roughness reduction of various roughness parameters after each LP processing step and (B) measured Sa values after each LP step.

figure that the surfaces after the second and fourth steps (smoothing) are much smoother, with less variation in the heightmaps, and clear appearance. Figure 3 C and E were taken with much lower illumination due to the increased reflectivity. The final surface shows no evidence of adhered particles or soot as is common on as-built AM surfaces.

**Table 3.** Settings for final LP strategy

| LP parameters | Step 1 *Ablation* | Step 2 *Smoothing* | Step 3 *Ablation* | Step 4 *Smoothing* |
|---|---|---|---|---|
| Scan speed (mm/s) | 620 | 325 | 620 | 325 |
| Hatch distance (μm) | 3.3 | 3.7 | 3.3 | 3.7 |
| Pulse width (ns) | 15 | 220 | 15 | 220 |
| Pulse frequency (kHz) | 290 | 100 | 290 | 100 |
| Focus offset (mm) | −0.38 | −1.34 | −0.38 | −1.34 |
| Fluence (J/cm$^2$) | 13.72 | 11.94 | 13.72 | 11.94 |
| Pulse overlap X (%) | 94 | 95 | 94 | 95 |
| Pulse overlap Y (%) | 91 | 94 | 91 | 94 |
| Number of passes | 8 | 8 | 4 | 14 |

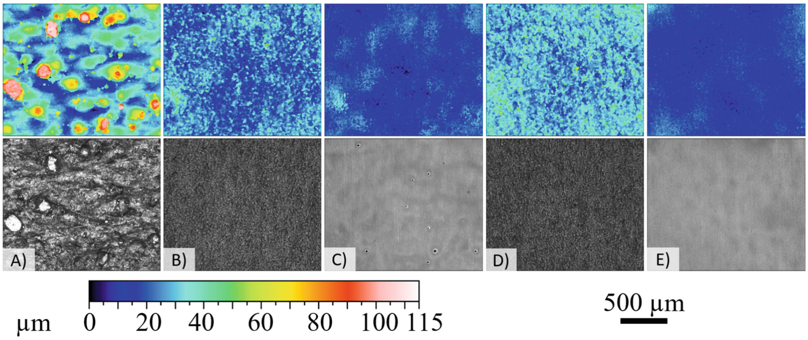



**Fig. 3.** Height maps (top) and optical images (bottom) of (A) the initial surface, and (B-E) after successive processing steps (Steps 1–4).

The minimum roughness values achieved with the developed LP strategy were 1.81 µm Sa, 12.8 µm Sp, 12.2 µm Sv, and 23.7 µm S10z. The corresponding maximum roughness reductions for each surface parameter were 94.1%, 91.6%, 83.5%, and 89.8% respectively. While evaluating the repeatability of the LP strategy in improving the surface finish it was noticed that the roughness reduction was lower at lower initial roughness values, as can be seen from Fig. 4. It has previously been reported by Hofele et al. [16] that their strategy was agnostic towards the initial surface roughness of parts. This was determined based on the average roughness values of surfaces built at various inclinations. Conversely, the present study shows that there is a relationship when considering the roughness of the same surface region before and after LP. Figure 4 shows the roughness reduction data, along with an inferred trend and 95% confidence bounds for that trendline.

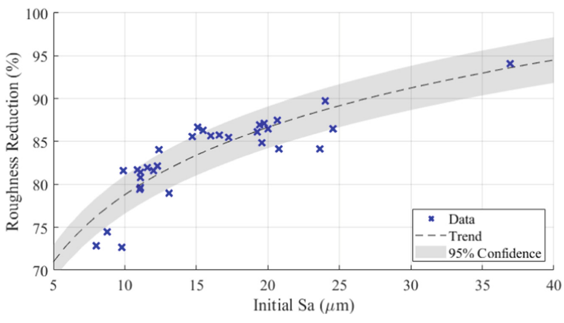



**Fig. 4.** Trend showing the relationship between the roughness reduction after LP and the initial roughness values.

## 4.2 Sub-surface Porosity

From the cross-sectional micrographs (Fig. 5 (A)) it can be seen that there is an increase in the porosity concentration just below the melted layer (40–50 µm depth) after LP. This is possibly because the material flow during the smoothing step could not fully cover the ablated surface, trapping air beneath. The maximum dimensions of pores observed were 40 × 30 μm. Using the ImageJ image processing software, the porosity between the surface and 100 μm below the surface was estimated to be 5.8%, much higher than the 2.2% found in the bulk material.

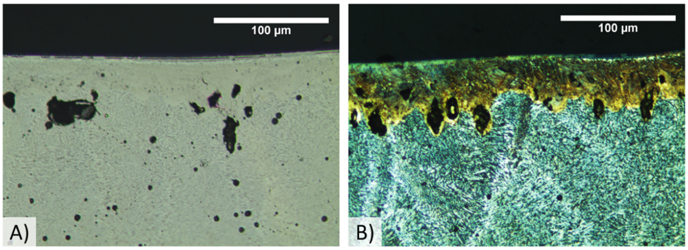



**Fig. 5.** Micrographs of (A) the surface region showing the sub-surface porosity, and (B) after etching to reveal the microstructure of the sub-surface region after the final LP step.

### 4.3 Microhardness

Figure 6 shows the microhardness data at various depths below the LP surface. It is observed that there is a slight increase in hardness beneath the LP surface (20% up to 10 μm depth) increasing to a maximum of 182 $HV_{0.01}$ between 30 and 40 μm depth. The bulk hardness of 105 $HV_{0.01}$ is achieved at depths greater than 50 μm. This is similar to findings by Bhaduri et al. [14] where surface hardening was observed following LP. The increase in the sub-surface hardness is possibly due to the enrichment of the silicon phases towards the surface [14]. However, unlike [14], no softer heat affected zone (HAZ) beneath the harder sub-surface layer is seen in the current study. Further investigations on the material compositions in the sub-surface layers after LP is under progress.

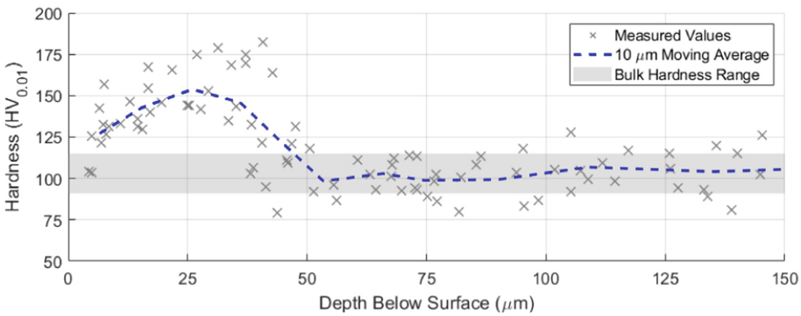



**Fig. 6.** Graph showing microhardness at different depths below the LP surface.

### 4.4 Microstructure

As described in Sect. 2.2, one aim for LP is to reflow surface material from asperities into depressions to achieve a smoother surface. The evidence of this can be seen Fig. 5 (B) where the striations beneath the LP surface indicates successive layers of material have been deposited with each laser pass. Below this, a darker region exists, resulting from the proceeding ablation step (step 3). The unaffected region shows the typical fish-scale structures originated from the melt-pools of the L-PBF process.

## 5 Conclusions

The developed multi-step laser polishing strategy has proven to be effective at reducing the surface roughness (up to 94.1% reduction in Sa) of AM AlSi10Mg parts. The strategy combines ablation and smoothing steps to minimise the residual roughness by targeting different aspects of the surface parameters. Clear evidence of material redistribution is seen in the cross-sectional micrographs. A correlation between the initial surface roughness and roughness reduction due to LP is also revealed.

The LP strategy results in an increased hardness (up to 23% higher) between the surface and 60 μm depth (maxima at 40–50 μm) before bulk hardness is achieved. However, there is an increase in porosity concentration just below this hardened layer (5.8% compared to 2.2% in the bulk). This increased porosity is thought to be due to air being entrained in the surface after the ablation steps and trapped by the flowing molten material during the smoothing steps. The success of the developed LP strategy will be further implemented in large-scale post-processing of AM parts for functional applications in automotive and aerospace industry.

**Acknowledgements.** This research is supported by the EPSRC Doctoral Training Programme. Thanks are due to the Cardiff University's technical staff team during sample preparation. Special thanks are for Dr P. Penchev of the University of Birmingham and Prof R. Leach of the University of Nottingham for their valuable advice during the project. Special thanks must go to Dr F. Lacan for manufacturing the samples used throughout.

## References

1. Hofele, M., et al.: Process parameter dependencies of continuous and pulsed laser modes on surface polishing of additive manufactured aluminium AlSi10Mg parts. Materwiss. Werksttech. **52**, 409–432 (2021). https://doi.org/10.1002/mawe.202000335
2. Whitehouse, D.J.: Surfaces and their Measurement. Kogan Page Science, London (2004)
3. Brandão, A.D., et al.: Fatigue properties of additively manufactured AlSi10Mg-surface treatment effect. Procedia Struct. Integr. **7**, 58–66 (2017). https://doi.org/10.1016/j.prostr.2017.11.061
4. du Plessis, A., Beretta, S.: Killer notches: the effect of as-built surface roughness on fatigue failure in AlSi10Mg produced by laser powder bed fusion. Addit. Manuf. **35**, 101424 (2020). https://doi.org/10.1016/j.addma.2020.101424

5. Calignano, F.: Investigation of the accuracy and roughness in the laser powder bed fusion process. Virtual Phys. Prototyp. **13**, 97–104 (2018). https://doi.org/10.1080/17452759.2018.1426368
6. Fox, J.C., Moylan, S.P., Lane, B.M.: Effect of process parameters on the surface roughness of overhanging structures in laser powder bed fusion additive manufacturing. Procedia CIRP. **45**, 131–134 (2016). https://doi.org/10.1016/j.procir.2016.02.347
7. Thijs, L., Kempen, K., Kruth, J.P., Van Humbeeck, J.: Fine-structured aluminium products with controllable texture by selective laser melting of pre-alloyed AlSi10Mg powder. Acta Mater. **61**, 1809–1819 (2013). https://doi.org/10.1016/j.actamat.2012.11.052
8. Wyatt, H., Elliott, M., Revill, P., Clarke, A.: The effect of engineered surface topography on the tribology of CFR-PEEK for novel hip implant materials. Biotribology. **7**, 22–30 (2016). https://doi.org/10.1016/j.biotri.2016.08.001
9. Xu, W.L., Yue, T.M., Man, H.C., Chan, C.P.: Laser surface melting of aluminium alloy 6013 for improving pitting corrosion fatigue resistance. Surf. Coatings Technol. **200**, 5077–5086 (2006). https://doi.org/10.1016/j.surfcoat.2005.05.034
10. Bhaduri, D., et al.: Laser polishing of 3D printed mesoscale components. Appl. Surf. Sci. **405**, 29–46 (2017). https://doi.org/10.1016/j.apsusc.2017.01.211
11. Renishaw plc.: AlSi10Mg-0403 powder for additive manufacturing, www.renishaw.com/additive (2015)
12. Materion Microelectronics & Services: Reflectance in Thin Films (2007)
13. Zhang, D. et al.: Investigation of laser polishing of four selective laser melting alloy samples. Appl. Sci. **10**(3), 760 (2020). https://doi.org/10.3390/app10030760
14. Bhaduri, D., et al.: Pulsed laser polishing of selective laser melted aluminium alloy parts. Appl. Surf. Sci. **558**, 149887 (2021). https://doi.org/10.1016/j.apsusc.2021.149887
15. Zhou, J., et al.: In-situ laser polishing additive manufactured AlSi10Mg: effect of laser polishing strategy on surface morphology. Roughness Microhardness. Mater. (Basel) **14**, 1–19 (2021). https://doi.org/10.3390/ma14020393
16. Hofele, M., et al.: Laser polishing of laser powder bed fusion AlSi10Mg parts—influence of initial surface roughness on achievable surface quality. Mater. Sci. Appl. **12**, 15–41 (2021). https://doi.org/10.4236/msa.2021.121002
17. Petkov, P.V., Penchev, P., Lacan, F., Bigot, S.: Finishing of Titanium ALM parts by Laser Ablation. In: WCMNM 2018 World Congress on Micro and Nano Manufacturing, pp. 111–114. Research Publishing Services, Singapore (2018). https://doi.org/10.3850/978-981-11-2728-1_85
18. Danzl, R., Helmli, F., Scherer, S.: Focus variation - a robust technology for high resolution optical 3D surface metrology. Stroj. Vestnik/J. Mech. Eng. **57**, 245–256 (2011). https://doi.org/10.5545/sv-jme.2010.175

# A Comparative Study of Pulse Wave and Continuous Wave Laser Patterns During Laser Powder Bed Fusion

Jun Song[1,2], Qian Tang[1](✉), Rossitza Setchi[2], and Michael Ryan[2]

[1] State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing 400044, China
tqcqu@cqu.edu.cn

[2] Cardiff School of Engineering, Cardiff University, Cardiff CF24 3AA, UK

**Abstract.** Laser powder bed fusion (LPBF) of metallic components is used across a wide range of industrial domains. Commercial LPBF machines utilise pulse or continuous laser systems; however, research on the underlying physical phenomenon in the pulse wave mode remains limited. Here, we developed a powder-scale computational fluid dynamics (CFD) multi-physics model to reveal the effect of the pulse wave mode on the thermal behaviour and molten pool evolution of 18Ni-300 maraging steel during LPBF. A model was also developed under the equivalent continuous wave mode to reveal the differences between these two modes. The results indicated that a fish-scale surface morphology of the melted track formed under the pulse wave mode, with deep penetration of the laser energy underneath the baseplate material. The instability of the molten pool in the pulse wave mode led to the formation of keyhole pores. Quantitative analysis showed that the molten pool was deeper and narrower under the pulse wave mode than under the equivalent continuous wave mode. The maximum temperature of the molten pool was significantly higher than the boiling point in both modes. The temperature slightly fluctuated under the continuous wave mode; however, a significant temperature drop occurred under the pulse wave mode when the laser source was switched off within one pulse. These findings demonstrated that the simulations developed for the continuous wave mode do not accurately model the equivalent pulse wave mode. This study also offers initial insights into the thermal and molten pool behaviours during pulse wave LPBF.

**Keywords:** Laser powder bed fusion · Pulse and continuous wave · Computational fluid dynamics (CFD) · Molten pool · Temperature history

## 1 Introduction

Laser powder bed fusion (LPBF) is an advanced metal additive manufacturing process that has been extensively employed in recent years in many industrial domains, including aerospace, automotive and medical industries [1]. Its main benefit is that it provides the ability to fabricate complex components directly from raw powder materials [2]. During processing, the powder material particles are selectively melted by a high-energy laser


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 283–290, 2023.
https://doi.org/10.1007/978-981-19-9205-6_27

source and then rapidly solidified, and the final components can be obtained by repeating this process layer by layer [3]. The extremely rapid melting and solidification rate during LPBF generates as-fabricated components that have a very fine microstructure compared with conventionally built components.

The laser system is a very significant part of any LPBF machine, as it directly influences the quality of the final components. Two laser types are widely employed in the commercial LPBF systems: continuous wave lasers and pulse wave lasers. Figure 1 shows the schematic diagram of the two LPBF laser system types and their scanning patterns. As their names suggest, the continuous wave laser mode continuously provides an energy input during processing, whereas the pulse wave laser mode outputs the energy intermittently by modulating the laser emission within a short period. Numerous industrial machine manufacturers, including SLM solutions, EOS, Concept laser, and Realizer SLM, use continuous wave laser systems extensively in their commercial LPBF machines, whereas a smaller number of machine manufacturers, including Renishaw, employ pulse wave laser systems [4]. The temporal distribution of the applied energy of the laser source is a significant parameter during pulse LPBF. Research suggests that, compared to the continuous laser mode, the pulse laser mode has greater advantages in manufacturing finer geometries, such as thin-walled [5] and lattice structures [6].

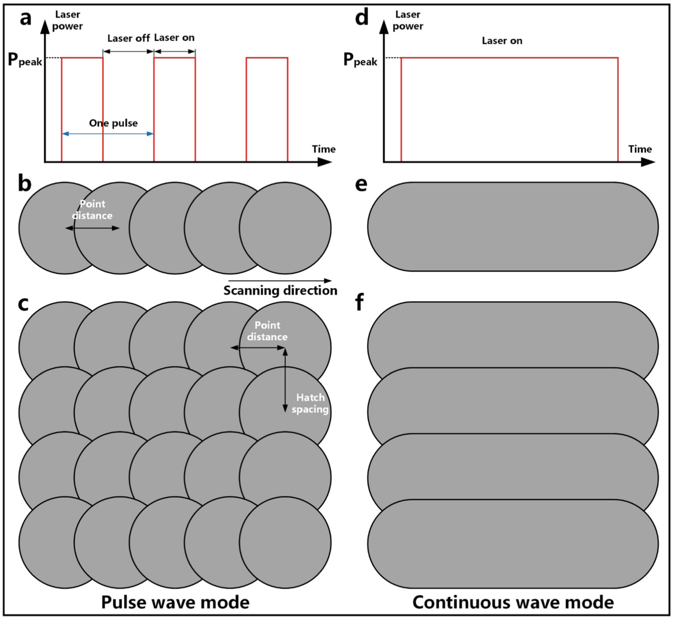



**Fig. 1.** Schematic diagram of the different laser system types and the scanning patterns used during LPBF: (a–c) pulse wave mode; and (d–f) continuous wave mode

Several experimental studies have explored the pulse wave LPBF, with a focus on the process parameters, microstructure, performance and dimensional accuracy. For example, Vecchiato et al. [7] studied the correlation between the molten pools and laser power, exposure time and energy input of 316L stainless steel during pulse wave LPBF. They found that the laser penetration depth into the materials was determined by the combination of laser power and exposure time. Different melting modes can be also obtained by varying the laser power under the constant input energy. Demir et al. [8] studied the effect of various exposure times and pulse overlaps on the resulting part quality produced from pulse wave LPBF-built 18Ni-300 maraging steels. They found that the relative density was improved by increasing the duty cycle by 3%. Georgilas et al. [9] studied the effect of various process parameters on the microstructure and mechanical properties of LPBF-built Inconel 718 fabricated under the pulse wave mode. Their experimental results revealed that the pulse wave mode generated more homogeneous grains and better mechanical behaviours than were achieved with the continuous wave mode. Kaschel et al. [5] compared the differences in dimensional accuracy, porosity and mechanical properties of Ti-6Al-4V parts between pulse and continuous wave LPBF. They found that under the same laser energy input, the tensile strength was higher for continuous wave as-built samples than for pulse wave as-built ones, but the pulse wave LPBF could improve the dimensional accuracy when manufacturing fine structures.

In addition to this previous experimental research, several studies have focused on the simulation of pulse LPBF. For example, Han et al. [10] developed a finite element model to predict the temperature behaviours of Al-$Al_2O_3$ composites during LPBF under the pulse laser mode; however, their models used the equivalent continuous wave mode by calculating the continuous scanning speed. Li et al. [11] introduced a 3D transient numerical model to study the effect of exposure time and point distance on the thermal behaviour during pulse wave LPBF of AlSi10Mg; however, their model used equivalent solid materials as the powder bed and ignored the effect of process parameters on the molten pool flows during processing. Zheng et al. [12] developed a mesoscale model for a comparative study of the molten pool dynamics of Inconel 625 during LPBF under both continuous and pulse laser modes. Their simulation results indicated that the surface morphology differed between these two modes, as the pulse laser mode resulted in a regular fish-like morphology, while the continuous laser mode gave a smooth surface morphology. That paper, to some extent, verified that the process experienced different thermal and fluid behaviours between pulse and continuous laser modes during processing, even under the same energy density condition. Similarly, the numerical models developed by Ding et al. [13] for studying the heat transfer and fluid flow behaviours during pulse and continuous wave LPBF of AlSi10Mg revealed a higher temperature and a larger molten pool size under the pulse wave mode when the same energy was applied.

The current literature indicates that the previous publications on pulse wave LPBF were focused mainly on experimental studies; therefore, knowledge regarding the numerical simulation of pulse wave LPBF is presently lacking. Accordingly, the aim of the present paper was to develop a powder-scale computational fluid dynamics (CFD) model that would allow a comparative investigation of the thermal and molten pool behaviours under pulse and continuous wave modes during LPBF.

## 2 Methodology

### 2.1 Process Parameters

As shown in Fig. 1, the pulse and continuous wave modes use different key parameters. Specifically, the key parameters of the pulse laser mode include laser power, exposure period, pulse distance and hatch spacing, whereas the key parameters of the continuous laser mode are laser power, scanning speed and hatch spacing. The laser energy density (LED) is extensively used to correlate with various parameters in both modes. The LED under the continuous wave mode is defined as [14]:

$$E = \frac{P}{v \cdot h \cdot d} \tag{1}$$

where $E$ is the LED, and $P$, $v$, $h$, and $d$ are laser power, scanning speed, layer thickness and hatch spacing, respectively.

The LED definition for the pulse laser mode differs due to differences in the key parameters. The LED under pulse wave mode is calculated by [5]:

$$E = \frac{P \cdot t_{on}}{d_p \cdot h \cdot d_h} \tag{2}$$

where $E$ is the LED, and $P$, $t_{on}$, $d_p$, $h$, and $d_h$ are the laser power, laser exposure time, point distance, layer thickness, and hatch spacing, respectively. The laser movement speed from one pulse to the next and the corresponding time when the laser is switching off ($t_{off}$) are generally set as constant values. In the Renishaw AM250 machine employed in the present study, these two parameters were maintained at 5 m/s and 20 μs, respectively.

### 2.2 Numerical Modelling

A CFD multi-physics model was developed for pulse and continuous wave modes during LPBF. The dimension of the computational domain used in this study was 1000 × 210 × 220 μm$^3$. The domain was uniformly meshed with a cell size of 5 μm, resulting in a total mesh number of 369600. For the implementation of the developed model, ANSYS Fluent v19.2 was used to solve the transport equations.

The process parameters used for the simulation of the pulse laser mode were as follows: the laser power and layer thickness were 160 W and 40 μm, respectively, while the exposure time and point distance were set as 80 μs and 65 μm, respectively. For comparison, the scanning speed (650 mm/s) for the equivalent continuous laser mode was calculated by:

$$v = \frac{d_p}{t_{on} + t_{off}} \tag{3}$$

# 3 Results and Discussion

## 3.1 Molten Pool Evolution

Figure 2 shows the simulated molten pool evolution under the pulse and continuous wave modes. The top-view morphologies of the simulated track at 1000 μs under both laser modes were continuous (Fig. 2a and d). Some fish-scale solidification phenomena were observed under the pulse laser mode, whereas the melted track of the continuous laser mode was smooth. Zheng et al. [12] also observed similar results in their modelling of the pulse LPBF of Inconel 625. They ascribed the formation of fish scales to the periodic change in the molten pools during pulse LPBF.

The cross-sections along the laser beam centre showed a depression region in the molten pool front under both modes; however, the depression depth was much larger under the pulse wave mode than under the continuous wave mode (Fig. 2b and e). The formation of the depression during processing was attributed to the evaporation-induced recoil pressure of the metal materials when the temperature was higher than the boiling temperature [15]. This observation suggested that a greater recoil pressure could be formed during pulse wave LPBF than during continuous wave LPBF. The cavity could collapse because of the instability of the molten pool when a strong recoil pressure is formed; therefore, a keyhole pore could form after solidification of the liquid metal. Hojjatzadeh et al. [16] also reported that the collapse of the depression would occasionally result in pores when the laser beam switched off at the end of the laser-on period in one cycle during pulse wave LPBF. A spherical keyhole pore was observed under the pulse wave mode in the present study, as shown in Fig. 2b and c.

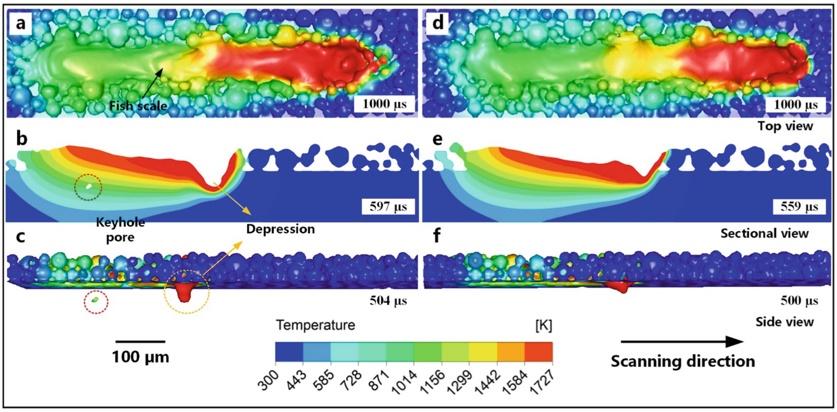



**Fig. 2.** Temperature distribution and molten pool evolution under different laser modes: (a–c) pulse wave mode; and (d–f) continuous wave mode

Figure 3 shows the simulated dimensions of the molten pools under the pulse and continuous wave modes during processing. The molten pool length under both modes was similar, with a value of approximately 240 μm, whereas the width of the molten pool was slightly lower under the pulse wave mode than under the continuous wave mode. The width of the molten pool was approximately 75 μm for the pulse mode and 85 μm for the continuous wave mode, indicating that a narrower molten pool can be obtained under the pulse wave mode. However, both the depression and the depth were higher under the pulse wave mode than under the continuous wave mode. The depression decreased from 35.3 μm to 18.5 μm under the pulse wave mode, while the depth reduced from 42.8 μm to 28.3 μm. These pronounced drops suggested that the laser energy can penetrate deeper during pulse LPBF.

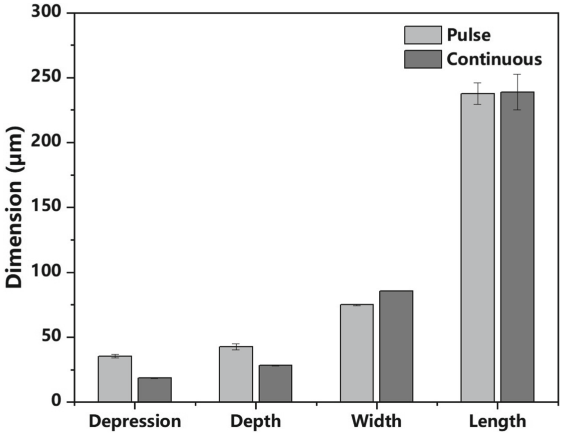



**Fig. 3.** Simulated molten pool dimensions under the pulse wave and continuous wave modes

## 3.2 Molten Pool Temperature History

Figure 4 shows the simulated maximum molten pool temperature versus time extracted from the computational domain under the pulse and continuous laser modes. This result was helpful for estimating the difference in the thermal behaviour between the two modes during processing. The two modes showed different thermal behaviour. For the continuous wave mode, the maximum temperature of the molten pool greatly exceeded the boiling point of 18Ni-300 maraging steel after the rapid increase in temperature at the beginning of the simulation. Owing to the instability of the laser during processing, the maximum temperature fluctuated slightly at around 3500 K. However, the periodic laser energy applied under the pulse laser mode led to a great drop in temperature when the laser was switched off within one cycle. During this laser-off period, the maximum temperature was approximately 2700 K, suggesting that some areas within the molten pools remained in the liquid state before the start of the next cycle. Note also that the different heating and cooling processing during the pulse wave mode could result in the formation of different microstructure than was formed with the continuous wave mode. This should be studied further in future work.

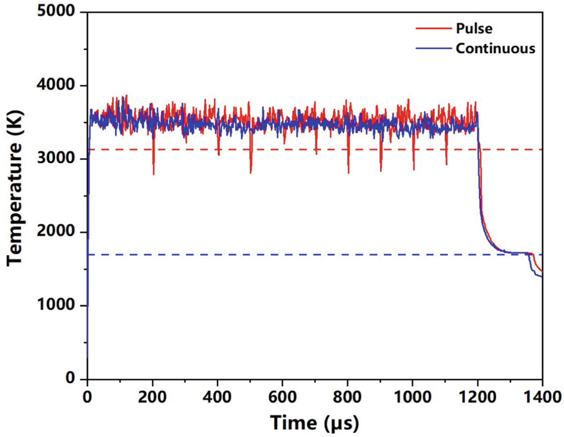



**Fig. 4.** Simulated maximum temperatures captured in the molten pools under the pulse and continuous wave modes

# 4 Conclusions

Single-track CFD multi-physics models were developed for a comparative investigation of the differences in the thermal behaviours between the pulse wave mode and the continuous wave mode during LPBF. The following conclusions were drawn from the findings of the single-track simulations:

(1) Different solidification phenomena can be observed under pulse and continuous wave modes during LPBF. Fish scales were observed under the pulse laser mode, whereas the melted track was smoother under the continuous laser mode. In addition, the laser energy can penetrate deeper underneath the baseplate material under the pulse wave mode than under the equivalent continuous wave mode. Due to the instability of the molten pool, a recoil pressure–induced keyhole pore was formed under the pulse wave mode.
(2) Quantitatively, the length of the molten pool was similar but the width was slightly narrower under the pulse wave mode than under the equivalent continuous wave mode. However, the depression and depth of the molten pool was much larger under the pulse wave mode. This result indicated that a narrower and deeper molten pool can be obtained during pulse wave LPBF. In addition, the maximum temperature fluctuated slightly under the continuous wave mode, whereas a great drop in temperature occurred when the laser was switched off within one pulse under the pulse wave mode.

In summary, this study provides a fundamentally new understanding of the differences in the thermal behaviours between pulse wave and continuous wave modes during LPBF. The study findings also proved that simulations developed for the continuous mode cannot accurately model the equivalent pulse wave mode. Future work will focus on studying the effect of different conditions on the thermal behaviours and molten pool dynamics during pulse LPBF.

**Acknowledgements.** This paper was supported by the National Natural Science Foundation of China (Grant No.: 51975073) and the China Scholarship Council (CSC).

## References

1. Gu, D., Shi, X., Poprawe, R., Bourell, D.L., Setchi, R., Zhu, J.: Material-structure-performance integrated laser-metal additive manufacturing. Science. **372**, eabg1487 (2021)
2. Song, J., Tang, Q., Feng, Q., Ma, S., Guo, F., Han, Q.: Investigation on the modelling approach for variable-density lattice structures fabricated using selective laser melting. Mater. Des. **212**, 110236 (2021)
3. Khairallah, S.A., et al.: Controlling interdependent meso-nanosecond dynamics and defect generation in metal 3D printing. Science **368**(6491), 660–665 (2020)
4. Biffi, C.A., Fiocchi, J., Bassani, P., Tuissi, A.: Continuous wave vs pulsed wave laser emission in selective laser melting of AlSi10Mg parts with industrial optimized process parameters: Microstructure and mechanical behaviour. Addit. Manuf. **24**, 639–646 (2018)
5. Kaschel, F.R., Keaveney, S., Dowling, D.P.: Comparison between continuous and modulated wave laser emission modes for the selective laser melting of Ti-6Al-4V: dimensional accuracy, microstructure and mechanical behaviour. Addit. Manuf. **55**, 102825 (2022)
6. Karami, K., et al.: Continuous and pulsed selective laser melting of Ti6Al4V lattice structures: effect of post-processing on microstructural anisotropy and fatigue behaviour. Addit. Manuf. **36**, 101433 (2020)
7. Vecchiato, F.L., de Winton, H., Hooper, P.A., Wenman, M.R.: Melt pool microstructure and morphology from single exposures in laser powder bed fusion of 316L stainless steel. Addit. Manuf. **36**, 101401 (2020)
8. Demir, A.G., Colombo, P., Previtali, B.: From pulsed to continuous wave emission in SLM with contemporary fiber laser sources: effect of temporal and spatial pulse overlap in part quality. Int. J. Adv. Manuf. Technol. **91**(5–8), 2701–2714 (2017)
9. Georgilas, K., Khan, R.H.U., Kartal, M.E.: The influence of pulsed laser powder bed fusion process parameters on Inconel 718 material properties. Mater. Sci. Eng. A. **769**, 138527 (2020)
10. Han, Q., Setchi, R., Lacan, F., Gu, D., Evans, S.L.: Selective laser melting of advanced Al-Al2O3 nanocomposites: simulation, microstructure and mechanical properties. Mater. Sci. Eng. A. **698**, 162–173 (2017)
11. Li, Z., Li, B.-Q., Bai, P., Liu, B., Wang, Y.: Research on the thermal behaviour of a selectively laser melted aluminium alloy: simulation and experiment. Materials **11**(7), 1172 (2018)
12. Zheng, M., et al.: Surface morphology evolution during pulsed selective laser melting: numerical and experimental investigations. Appl. Surf. Sci. **496**, 143649 (2019)
13. Ding, X., Wang, L., Wang, S.: Comparison study of numerical analysis for heat transfer and fluid flow under two different laser scan pattern during selective laser melting. Optik (Stuttg). **127**, 10898–10907 (2016)
14. Song, J., et al.: Effect of heat treatment on microstructure and mechanical behaviours of 18Ni-300 maraging steel manufactured by selective laser melting. Opt. Laser Technol. **120**, 105725 (2019)
15. Tang, C., Tan, J.L., Wong, C.H.: A numerical investigation on the physical mechanisms of single track defects in selective laser melting. Int. J. Heat Mass Transf. **126**, 957–968 (2018)
16. Mohammad, S., et al.: In-situ characterization of pore formation dynamics in pulsed wave laser powder bed fusion. Materials **14**(11), 2936 (2021). https://doi.org/10.3390/ma14112936

# Towards Urban Symbiosis of Critical Raw Materials – A Conceptual Paper

Maria Antikainen[1](✉), Mona Arnold[1], Päivi Kivikytö-Reponen[1], and David Lazarevic[2]

[1] VTT Technical Research Centre of Finland, Espoo, Finland
maria.antikainen@vtt.fi
[2] Finnish Environment Institute, Helsinki, Finland

**Abstract.** Regions and national economies are facing several challenges regarding raw materials. As cities and metropolitan areas are increasingly becoming hubs of economic activity, they may also play a role in addressing raw material challenges. Many eco-industrial parks are not only found in industrial areas but also in urbanised areas the concept of *urban symbiosis* may offer viable solutions to those challenges. Urban symbiosis builds on urban and regional metabolism and industrial symbiosis, providing a concept and analytical toolkit that can serve to develop strategies to create the more efficient use and circulation of critical raw materials (CRM), enabled by the integration of different and complex systems. This paper aims to review how urban symbiosis of CRMs has been approached and defined in the prior literature and what are the closely related concepts. One of our key interest areas is to understand what kind of roles cities can have in the urban symbiosis. Based on the results, we suggest future research topics such as exploring concrete models of collaboration and new ways of joint value creation in urban symbiosis ecosystems.

**Keywords:** Urban symbiosis · Critical raw materials · Circular cities · Conceptual paper

## 1 Introduction

There is a major need to find efficient and innovative solutions to stem the loss of resources, including critical raw materials (CRMs), in the future economy. CRMs can be broadly defined as raw materials that are economically and strategically important for an economy but have a high-risk associated with their supply, which can include, for example, metals (e.g., tungsten, cobalt, magnesium), minerals (e.g., phosphorus) and gasses (e.g., helium) [1]. Applications that include CRMs are widely used in society, and notably, as these materials are needed in buildings, infrastructure, and high technology products nations need to secure access to CRMs. High-tech products are not often used efficiently, and their lifetime can be relatively short. As they are used predominantly in cities, the urban scale is an underexplored domain through which the societal value CRMs can be retained.


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 291–300, 2023.
https://doi.org/10.1007/978-981-19-9205-6_28

One viable solution for simultaneously minimising resource use and reducing pollution is the transition towards a circular economy (see [2]) through implementing the practice of urban symbiosis [3]. Prior research has shown that the circularity rate is not a sufficient indicator for optimising resource use and footprint minimisation. Instead, there is a need to combine different indicators, including the costs of different solutions and the evaluation of trade-offs [3].

## 1.1 Methodology: Conceptual Paper

The aim of the conceptual paper is to interlink and integrate existing theories and concepts, providing multidisciplinary insights into the phenomenon [9]. Thus, the focus is on creating a bridge between different theories, rather than creating a new theory. A conceptual paper is a relevant approach when exploring a new, complex multidimensional phenomenon. We start by describing the state-of-the-art and exploring relevant questions for further study [10].

This paper concentrates on creating an understanding of urban symbiosis for CRMs and the role of the cities. We acquired published empirical studies through Scopus, Web of Science, Science Direct, and Google Scholar using multiple keywords to identify relevant articles [11]. The keywords included "Urban symbiosis", "Industrial symbiosis", "Metabolism", "Critical raw materials", "Circular City" and their combinations.

We started with a systemic approach, encompassing the concepts in sustainability literature, which relate to urban symbiosis and what it makes part of. Figure 1 gives our understanding of the concepts. We included a special focus on the metabolism of CRMs, which can be embraced by both Industrial Symbiosis, Urban Symbiosis, and Urban Mining (Fig. 1).

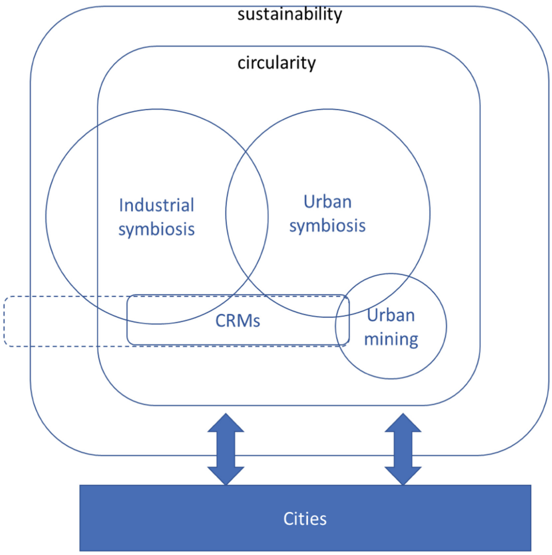



**Fig. 1.** Sustainability concepts relating to sustainable management of CRMs.

Taking a qualitative approach and using our prior knowledge, we selected the most relevant 33 articles. 28 were published in scientific journals (impact factor between 3–9), 3 in peer-reviewed books, and 2 in conference publications.

### 1.2 Aim of the Study

Our objective is to study *how the urban symbiosis of critical materials has been approached and defined in the prior literature and what are the closely related concepts*. A key interest is to understand what roles cities can take in urban symbiosis. The role of cities as urban scale actors in retaining the value of CRMs is understudied and hence requires more investigation. The paper is structured as follows. Section 2 provides a brief literature review of industrial symbiosis, urban symbiosis, cities, and CRMs. Section 3 provides our synthesis and areas identified for future research.

## 2 Literature Review

### 2.1 Industrial and Urban Symbiosis

**Industrial Symbiosis**

Industrial Symbiosis (IS) has been studied over the last 25 years, yet during the last five-ten years, IS seems to have found a renewed impetus within the context of the Circular Economy (CE) [12]. The term "symbiosis" derives from the biology describing two different organisms living in a community that benefits both. Frosch and Gallopoulos [13] stated that an industrial ecosystem could operate analogously to a biological ecosystem. They suggested that in such an industrial system, the use of energy and materials are optimized, as the amount of waste and pollution is minimised. Based on this idea, industrial symbiosis (IS) has become a core part of the industrial ecology (IE) field [14]. Whilst IE takes a multi-level focus—on global, regional, local, and enterprise levels [15]—IS concentrates on enterprise linkages [16] One well-known example of such linkages is the Kalundborg IS, started in 1961 in Denmark [17].

Chertow [15] defines IS "as part of the emerging field of industrial ecology, demands resolute attention to the flow of materials and energy through local and regional economies. Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving the physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity".

According to Chertow [15] input-output matching, stakeholder processes, and materials budgeting appear to be useful tools in advancing eco-industrial park development. Evolutionary approaches to industrial symbiosis are also found to be important in creating the level of cooperation needed for multi-party exchanges.

According to Momirski et al. [17], IS constitutes at minimum three companies that exchange at least two different sources creating a more circular than a linear process. Similar to Chertow's [15] approach, the collaboration between different industry partners has been identified as an essential element for IS to create environmental and economic benefits [16]. Successful IS is often based on collaboration and synergies resulting from geographical proximity [15].

Laybourn [18], extends this definition by arguing that IS is not only for industries but also can include organisations such as research and government actors. Lombardi and Laybourn [19] highlight IS role as a business opportunity and tool for eco-innovation. IS operates in a network of eco-innovation-minded organisations that exchange knowledge, drive the process for cultural change and improve technical and business processes aiming to find joint value creation models. They suggest that geographic proximity might not play a crucial role in the exchange of physical resources [19]. Above all they see IS as a tool for innovative green growth and, ecological benefits should be seen as a result, not the driver. Summarising the discussion in the IS literature, IS becomes a model of sustainability when it manages four pillars: 1) eco-efficiency, 2) collaboration, 3) adaptability, and 4) Proximity [20].

Based on the barriers and enablers in IE literature Golev et al. [21] have identified seven enablers and enablers to industrial symbiosis: 1) organisational commitment to sustainability at the strategic level, 2), information (qualitative and quantitative) about waste streams and local industries' material/water/energy requirements to provide the starting point for the development of resource synergies, 3) cooperation and trust between key players for sharing of information and network development, 4) technical feasibility and knowledge, 5) understanding regulatory and legal frameworks are the drivers for synergy projects, 6) community awareness of the environmental and economic impacts that industries generate, and 7) both the positive economic outcome along with environmental benefits concretising as increased revenue, lower input costs, lower operational costs, and diversifying and/or securing water, energy, and material supplies. Yet, adding to Golev et al.'s [21] work, the development of industrial symbiosis may require significant investments in companies at the same time as the economic benefits will take time before materialising companies' financial performance. Table 1 summarizes the most important journal articles that were used in the literature review.

**Urban Symbiosis**

Industrial symbiosis has been extended to the urban level, focusing on the exchange of urban waste and energy (Urban symbiosis). The concept of urban symbiosis was introduced only in 2009 by Van Berkel et al. [22, 23]. Thus, there are many more studies concentrating on IS or integrating IS and urban symbiosis perspectives than solely focusing on urban symbiosis [17]. Yet, cities are facing several challenges regarding raw materials, and because many industrial parks are not only industrial areas but also part of an urbanized urban area where people live, urban symbiosis can offer viable solutions to those challenges [14].

Urban symbiosis can be seen as an extension of IS and is defined as "the use of by-products (wastes) from cities (or urban areas) as alternative raw materials or energy sources in industrial operations" [17]. Much of the urban symbiosis emanates from Japan, where solid waste source separation systems are well established in municipal systems and uniquely suited to the Japanese core eco-urban program [24]. Van Berkel et al. [22] stress geographical location in their definition of urban symbiosis: "(it) covers specific possibilities arising from geographic proximity of urban and industrial areas to

**Table 1.** Definitions and perspectives on industrial symbiosis

| Definitions and perspectives to industrial symbiosis (IS) | Author |
|---|---|
| IS, as part of the field of industrial ecology, demands resolute attention to the flow of materials and energy through local and regional economies. IS engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to IS are collaboration and the synergistic possibilities offered by geographic proximity. | Chertow, 2000 |
| IS constitutes at minimum three companies that exchange at least two different sources creating more circular than linear process. | Momirski et al., 2021 |
| IS not only for industries but also can include organisations such as research and government actors. | Laybourn, 2006 |
| IS can also be seen as a business opportunity and tool for eco-innovation: IS operates in a network of eco-innovation minded organisations who exchange knowledge, drive the process for cultural change and improve technical and business processes aiming to find joint value creation models. Geographic proximity might not play a crucial role in the exchange of physical resources. | Lombardi and Laybourn, 2012 |
| IS becomes a model of sustainability when it managing four pillars: 1) eco-efficiency, 2) collaboration, 3) adaptability, 4) Proximity (Diemer, 2009). | Diemer, 2009 |
| Seven barriers/enablers to industrial symbiosis: Commitment to sustainable development , information, cooperation, technical, regulatory, community, economic | Golev et al., 2015 |

use physical resources discarded in urban areas ("wastes") as alternative raw material or energy source for industrial operations".

Both IS and urban symbiosis aims for waste recycling and a network of symbioses through feedstock savings and/or emissions reductions that provide obvious benefits to society as a whole [25]. The main difference between IS and urban symbiosis can be seen in the following way: as IS recognizes the exchange of waste resources and by-products between enterprises that do not normally cooperate in resource exchange; urban symbiosis recognizes the use of solid waste in cities as input sources for industries that do not normally accept these sources [25]. Urban symbiosis can be seen as a network of communities, in which industrial actors integrate the local needs to improve resource utilisation by exploring synergies in urban and industrial areas [26, 27]. Often the public sector facilitates the waste exchanges and firm/community interaction [28, 29].

Urban symbiosis is seen as a strategy toward more efficient metabolism of cities. To achieve urban symbiosis, the integration of several systems is needed, which often sets major challenges for renewing pre-existing systems and building new joint systems connecting novel areas. It can be stated that urban symbiosis is a physical, economic, and political challenge, but it also faces several other challenges including the complexity of managing the interests of all stakeholders involved [30]. Therefore, similar to IS, the collaboration between stakeholders plays a crucial role in enabling the transition towards urban symbiosis [7].

Reviewing sustainable urban development strategies for eleven cities, Momirski et al. [17] show that the awareness of IS and urban symbiosis is rising, and there already exists legislative support that is aligned with EU legislation. However, they show the reuse of by-products either for energy or new products is almost totally missing or plays a trivial role. Table 2 summarises the discussion and perspectives on urban symbiosis.

**Table 2.** Definitions and perspectives on urban symbiosis

| Definitions and perspectives to Urban Symbiosis | Author |
|---|---|
| Urban symbiosis can be seen as an extension of IS and is defined as the "the use of byproducts (wastes) from cities (or urban areas) as alternative raw materials or energy sources in industrial operations" | Dong, 2014 |
| The term urban symbiosis covers specific possibilities arising from geographic proximity of urban and industrial areas to use physical resources discarded in urban areas ("wastes") as alternative raw material or energy source for industrial operations. | Berkel et al., 2008 |
| Both IS and urban symbiosis aim for waste recycling and a network of symbioses through feedstock savings and/or emissions reductions that provide obvious benefits to society as a whole. The main difference between IS and urban symbiosis is that as IS recognizes the exchange of waste resources and by-products between enterprises that do not normally cooperate in resource exchange; urban symbiosis recognizes the use of solid waste in cities as input sources for industries that do not normally accept these sources. | Chen et al., 2011 |
| Urban symbiosis is seen as a strategy towards more efficient metabolism of cities. In order to reach urban symbiosis, integration of several systems is needed, which often sets major challenges for renewing pre-existing systems and start building new joint systems connecting novel areas. Urban symbiosis not only sets physical, economic, and political challenges, but it also faces several other challenges including the complexity of managing the interests of all stakeholders involved. | Mulder, 2017 |

## 2.2 Urban Symbiosis and Cities

### The Circular City

While industrial symbiosis is seen as a business-focused collaborative approach, the circular city plays a key role in evolving urban symbiosis systems. Cities consume about 75% of global resources, emit 50–70% of all greenhouse gases and generate 50–70% of global waste [31, 32]. Cities are, thus, a potential source of secondary materials and can play a significant role in recirculating critical resources, thereby supporting the resilience of societies and diminishing the extraction of virgin sources. Indeed, the EU Urban Agenda presents 12 priority themes concerning the crucial in the development of cities, one of which is circular economy (CE). City-level actions are seen as essential in encouraging businesses and consumers in adopting circular modes of thinking and doing, putting local governments in a unique position in facilitating a transition from a traditional linear economy to a more sustainable circular one (European Commission, 2021). Cities have a density and concentration of producing businesses and consuming citizens that generate material and resource flows with circular potential. Moreover, many cities also have a scale that, on the one hand, enables quick decisions, having the power to regulate and incentivise, and, on the other hand, is large enough to enable the establishment of new circular city functions and services, and circular business models

[32]. However, cities often tend to view themselves as facilitators, disinclined to risk the investment into new circular infrastructure themselves and provide little funding for CE initiatives [33].

Paiho et al. [34] pointed out in their conceptual work the lack of a single definition of a 'circular city', but several components of urban circularity have been proposed. The European Investment Bank has described a circular city as one that conserves and reuses resources and products, shares and increases the use and utility of all assets, and minimises resource consumption and wastage in all forms [32].

The International Council for Local Environmental Initiatives [35] defines a circular city as one that promotes a just transition from a linear to a circular economy across the urban space, through multiple city functions and departments and in collaboration with residents, businesses, and the research community. Moreover, Williams [36] highlighted seven circular strategies – looping, localisation, substitution of resource-intensive materials and products, adaptation, sharing, optimising, and regenerating natural capital to operate together to deliver the circular city.

**Cities' Role in Urban Symbiosis**

With the increased resources being concentrated in cities, they can be seen as urban mines. With the increasing amount of waste generated within cities, the city as an urban mine creates the market potential for recovered materials. Moreover, considering the metal criticality, the importance of extending the lifetime of products containing CRMs, and recovering and recycling CRMs containing waste gathered in urban mines is increasing [37]. In this context, the collection of waste electrical and electronic equipment (WEEE), the main urban flow containing critical metals, has achieved much attention lately. The significance of this potential resource will also likely increase with shifts concerning energy production and consumption.

With the regeneration of cities, acceleration of renewable energy production technologies, including wind and solar technologies, has taken place, and, related to this trend, new technologies for more efficient electricity consumption patterns have emerged [38]. With increasing smartness, relating i.e. to energy use, cities are also becoming more reliant on the use of critical raw material [39].

## 2.3 Critical Raw Materials

Ensuring a sufficient raw material supply to meet demand is seen as economically important in many countries and regions. In Europe, EU level CRM listing arises from the growing concern of securing valuable raw materials for the EU economy. The actions taken to support raw materials supply, the European Raw Materials Initiative was launched in 2008, followed by establishment of a list of CRMs at the EU level.

The needs, economic importance, and geopolitical relations evolve, leading to updates. The current (fourth) list (2020) contains 30 CRMs that are particularly important for high-tech products and emerging innovations and therefore of high economic concern [40]. For example, transitioning to a low carbon society with low carbon technologies and to a data economy with increased digitalization will entail an increased use in CRMs containing components such as batteries, magnets, PCBs, etc.

The EU methodology for CRMs relies on a criticality assessment of raw materials. In this assessment, supply risk is considered to be related to recycling (End-of-Life Recycling Input Rate), substitutability (Substitution Index), and the Herfindahl Hirschman Index [41]. Actions minimizing supply risk taken through secondary raw materials and substitution are widely used and actions to increase the overall circularity of CRMs may substantially reduce supply risk. Actions taken to support life-time extension through circular economy business models would both decrease the need for new products, and CRMs and support the collection and proper cycling of CRMs.

## 3 Conclusions and Future Research Areas

The literature review highlighted several perspectives on urban symbiosis. Urban symbiosis is a strategy toward a more efficient metabolism of cities and, thus, can offer significant sustainability improvements. However, significant challenges (such as physical, ecological, political challenges, and stakeholder involvement) must be overcome (e.g. [42]).

Our proposition for urban symbiosis builds on urban and regional metabolism (see [4, 5]) and industrial symbiosis [6], serving as a concept and analytical toolkit to develop strategies for the efficient use and circulation of CRMs enabled by the integration of different and complex systems (cf. [7]). Urban symbiosis starts with understanding the metabolism of CRMs—how CRMs flow through cities and their different systems—and moves beyond an empirical exercise, analysing CRMs flows through cities wealth-creating subsystems to develop novel business ecosystems. Urban symbiosis emphasises the disruptive value-adding collaborative models, and resource dependencies between businesses, organisations, and consumers within cities.

For CRMs in high technology products, the urban symbiosis approach starts with understanding the metabolism of CRMs and the actors involved in their governance (public, private, and consumers) and then developing business ecosystems, circular supply chains, and city-level policy strategies that are tailored to their institutional context. Urban symbiosis emphasises the resource dependencies between actors within a city and, thus, a need for the co-evolution of institutionally embedded value co-creation and policy process [8]. Urban symbiosis would offer a possibility to increase the sustainable circularity of CRMs through city-level actions, notwithstanding the global nature of supply chains and the systemic changes required.

There are several barriers and enablers identified in the IS context, and many of them also apply to the urban symbiosis context (e.g. [21]). For example, the role of collaboration between different stakeholders is highlighted in both IS and urban symbiosis contexts and CE in general. Thus, the concrete models of collaboration to accelerate the urban symbiosis of CRMs requires further research area. The role of the city in accelerating the transition towards circularity and models for collaboration and common interests of private companies and public organisations also requires investigation. Understanding of different value creation models for different actors as well as the sustainable value in general in urban symbiosis-based ecosystems would be needed to accelerate the transition process. Furthermore, more research and understanding, in general, is needed on the real cases, barriers, and enablers in implementing urban symbiosis of CRMs to create a concrete understanding of the phenomenon.

## References


1. Ferro, P., Bonollo, F.: Materials selection in a critical raw materials perspective. Mater. Des. **177**, 107848 (2019)
2. Lazarevic, D., Brandão, M.: The circular economy: a strategy to reconcile economic and environmental objectives? In: Brandão, M., Lazarevic, D., Finnveden, G. (eds.) Handbook of the Circular Economy, pp. 8–27. Edward Edgar Publishing, Cheltenham (2020)
3. Gai, L., Varbanov, P.S., Huin Chin, H., Jaromír Klemeš, J., Nižetić, S.: Targeting and optimisation of industrial and urban symbiosis for circular economy. Comput. Aided Chem. Eng. **50**, 1659–1664 (2021)
4. Kennedy, C., Cuddihy, J., Engel-Yan, J.: The changing metabolism of cities. J. Ind. Ecol. **11**, 43–59 (2007). https://doi.org/10.1162/jie.2007.1107
5. Buclet, N.: Territorial Ecology and Socio-ecological Transition. ISTE/Wiley, London (2021)
6. Chertow, M.R.: "Uncovering" industrial symbiosis. J. Ind. Ecol. **11**, 11–30 (2007)
7. Vernay, A.L., Mulder, K.F.: Organising urban symbiosis projects. Proc. Inst. Civ. Eng. Eng. Sustain. **169**, 181–188 (2016)
8. Lazarevic, D., Valve, H.: Narrating expectations for the circular economy: towards a common and contested European transition. Energy Res. Soc. Sci. **31**, 60–69 (2017). https://doi.org/10.1016/j.erss.2017.05.006
9. Cropanzano, R.: Writing nonempirical articles for Journal of Management: general thoughts and suggestions. J. Manage. **35**, 1304–1311 (2009)
10. Gilson, L.L., Goldberg, C.B.: Editors' comment: so, what is a conceptual paper? Gr. Organ. Manag. **40**, 127–130 (2015)
11. Mowery, D.C., Oxley, J.E., Silverman, B.S.: Strategic alliances and inter-firm knowledge transfer. Strateg. Manag. J. **17**, 77–91 (1996)
12. Cecchin, A., Salomone, R., Deutz, P., Raggi, A., Cutaia, L.: Relating industrial symbiosis and circular economy to the sustainable development debate. In: Salomone, R., Cecchin, A., Deutz, P., Raggi, A., Cutaia, L. (eds.) Industrial symbiosis for the circular economy. SS, pp. 1–25. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-36660-5_1
13. Frosch, R.A., Gallopoulos, N.E.: Strategies for manufacturing. Sci. Am. **261**, 144–152 (1989)
14. Dong, L., et al.: Promoting low-carbon city through industrial symbiosis: a case in China by applying HPIMO model. Energy Policy **61**, 864–873 (2013)
15. Chertow, M.: Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy Environ. **25**, 313–337 (2000)
16. Ehrenfeld, J., Gertler, N.: Industrial ecology in practice: the evolution of interdependence at Kalundborg. J. Ind. Ecol. **1**, 67–79 (1997)
17. Momirski, L.A., Mušič, B., Cotič, B.: Urban strategies enabling industrial and urban symbiosis: the case of Slovenia. Sustainability. **13**, 4616 (2021)
18. Laybourn, P.: The development of the national industrial symbiosis program (NISP)—a case for publicly funded macro industrial symbiosis networks. Presented to Intelligent Made Future. Cambridge, UK (2006)
19. Lombardi, D.R., Laybourn, P.: Redefining industrial symbiosis. J. Ind. Ecol. **16**, 28–37 (2012)
20. Diemer, A.: Industrial symbiosis and European policy. In: Diemer, A., Morales, M.E. (eds.) European Union and Sustainable Development: Challenges and Prospects, pp. 235–258. Editions Oeconomia, Im-primerie Chaumeil, Clermont-Ferrand, France (2017)
21. Golev, A., Corder, G.D., Giurco, D.P.: Barriers to industrial symbiosis: Insights from the use of a maturity grid. J. Ind. Ecol. **19**, 141–153 (2015)
22. Van Berkel, R., Fujita, T., Hashimoto, S., Fujii, M.: Quantitative assessment of urban and industrial symbiosis in Kawasaki, Japan. Environ. Sci. Technol. **43**, 1271–1281 (2009)

23. Van Berkel, R., Fujita, T., Hashimoto, S., Geng, Y.: Industrial and urban symbiosis in Japan: analysis of the Eco-Town program 1997–2006. J. Environ. Manag. **90**, 1544–1556 (2009)
24. Geng, Y., Tsuyoshi, F., Chen, X.: Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. J. Clean. Prod. **18**, 993–1000 (2010)
25. Chen, X., Xi, F., Geng, Y., Fujita, T.: The potential environmental gains from recycling waste plastics: simulation of transferring recycling and recovery technologies to Shenyang, China. Waste Manag. **31**, 168–179 (2011)
26. Kurdve, M., Jönsson, C., Granzell, A.S.: Development of the urban and industrial symbiosis in western Mälardalen. Procedia CIRP **73**, 96–101 (2018)
27. Sun, L., et al.: Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: a case of Liuzhou city, China. Res., Conserv. Recycl. **119**, 78–88 (2017). https://doi.org/10.1016/j.resconrec.2016.06.007
28. Fraccascia, L., Giannoccaro, I., Albino, V.: Business models for industrial symbiosis: a taxonomy focused on the form of governance. Res., Conserv. Recycl. **146**, 114–126 (2019). https://doi.org/10.1016/j.resconrec.2019.03.016
29. Henriques, J., Ferrão, P., Castro, R., Azevedo, J.: Industrial symbiosis: a sectoral analysis on enablers and barriers. Sustainability **13**, 1723 (2021)
30. Mulder, K.: Urban symbiosis as a strategy for sustainabilising cities: an overview of options and their potential, pitfalls and solutions. Civ. Eng. Res. J. **2**, 1–7 (2017)
31. Lucertini, G., Musco, F.: Circular urban metabolism framework. One Earth **2**, 138–142 (2010)
32. EIB: The 15 circular steps for cities. European Investment Bank, Luxembourg (2021)
33. Prendeville, S., Cherim, E., Bocken, N.: Circular cities: mapping six cities in transition. Environ. Innov. Soc. Transitions. **26**, 171–194 (2018). https://doi.org/10.1016/j.eist.2017.03.002
34. Paiho, S., et al.: Towards circular cities—conceptualizing core aspects. Sustain. Cities Soc. **59**, 102143 (2020)
35. ICLEI: CIRCULAR CITY ACTIONS FRAMEWORK Bringing the circular economy to every city (2020)
36. Williams, J.: Circular Cities: Strategies, Challenges and knowledge gaps. Circ. Cities Hub. (2016)
37. Kotnis, J.: Critical raw materials in the city: Recycling perspectives for cobalt in the Hague (2018)
38. David, M., Koch, F.: "Smart is not smart enough!" anticipating critical raw material use in smart city concepts: the example of smart grids. Sustainability **11**, 4422 (2019)
39. Țăranu, A., La Forestra, D., Cerasuolo, A.: Critical raw materials and cities: a literature review. J. Urban Regen. Renew. **15**, 45–56 (2021)
40. European Commission: Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability. COM(2020) 474 final. (2020)
41. Blengini, G.A., et al.: EU methodology for critical raw materials assessment: policy needs and proposed solutions for incremental improvements. Resour. Policy. **53**, 12–19 (2017). https://doi.org/10.1016/j.resourpol.2017.05.008
42. Mulder, K.F.: Innovation for sustainable development: from environmental design to transition management. Sustain. Sci. **2**, 253–263 (2007)

# Modelling and Optimization of Interior Permanent Magnet Motor for Electric Vehicle Applications and Effect on Sustainable Transportation

Nurul Azim Bhuiyan(✉), Lavanya Balasubramanian, Ashraf A. Fahmy, Fawzi Belblidia, and Johann Sienz

ASTUTE 2020, Swansea University, Swansea, UK
n.a.bhuiyan@swansea.ac.uk

**Abstract.** Electric vehicles support low-carbon emissions that facilitate sustainable transportation. This paper explores different design parameters to optimize an interior permanent magnet synchronous motor that contributes to enhancing motor performance hence advancement of sustainable transportation. Various geometry parameters such as magnet dimension, machine diameter, stator teeth height, and number of pole pair are analysed to compare overall torque, power, and torque ripples in order to select the best design parameters and their ranges. Pyleecan, a comparatively new open-source software, is used to design and optimize the motor for electric vehicle applications. It is verified with Motor-CAD software to observe the performance of the Pyleecan software. Following optimisation with NSGA-II algorithm, two designs A and B were obtained for two different objective functions of maximizing torque and minimizing torque ripple and the corresponding torque ripples values of the design A and B are later reduced by 32% and 77%. Additionally, the impact of different magnet grades on the output performances are analysed.

**Keywords:** Eelectric vehicles · IPM motor · Magnet grade · Optimization · Permanent magnet motor · Torque ripple

## 1 Introduction

Electric vehicles (EV) are playing key role for clean energy and total emission reductions that helps sustainable transportation. It is a next-generation mobility technology to meet the global emission reduction targets especially those set out in the Paris Agreement [1] and the European Union (EU). The transition towards electrification of vehicles plays a crucial role in creating a greener and more sustainable future. Compared to classic internal combustion engines (ICE), electric motors used in EVs are significantly more efficient. Due to high efficiency and torque density, A growing proportion of electric vehicles are now based on Permanent Magnet (PM) motors. The most viable solutions in the automotive industry to reduce the environmental impacts of urban mobility, to


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 301–311, 2023.
https://doi.org/10.1007/978-981-19-9205-6_29

improve air quality, and to achieve emissions targets is optimization of electric vehicle motors with objectives of high torque and power densities, as well as producing low-cost solutions through materials and mass manufacturing capabilities [2]. Therefore, toensure the advancement of sustainable transportation highly efficient motor for electric vehicles is a key requirement.

One of the bottlenecks of interior permanent magnet synchronous motor (IPMSM) operation is known as the cogging torque [3]. The interaction between the stator teeth and rotor magnets, and the permeance variations during the magnet rotation lead to the production of cogging torque, which eventually lead to audible noise, vibration, fluctuation in speed, and the introduction of torque ripples. In case of motion control applications, these torque ripples result in significant deterioration of the motor performance and therefore, it is an important aspect to address. Multiple parameters have been identified in the literature [1, 4–6] to have an influence on torque ripples including slot pole combination [7], stator slot opening, slot width, slot height, notch radius [8], airgap length [9], stack length, pole numbers, magnet dimensions, magnet shape and position.

Various studies have explored this issue, and it is understood that one of the most common methods of combating this is by magnet skewing with surface mounted magnets [3, 10]. Magnet skewing involves dividing the magnet into layers and placing them in the rotor in different radial positions that vary by a small angle [11]. The major disadvantage of this method is that it increases cost and manufacturing complexity. Another method of skewing is the stator skewing. However, this complicates automatic winding, and it is not widely popular in mass manufacturing environments.

In order to address the torque ripples issue, an alternative solution has been proposed by optimizing parameters such as number of poles, magnet dimension, stator teeth height, and stator diameter.

The main purpose of this paper is to identify the best component sizing for a given set of requirements and to investigate the trade-offs between torque, power, and torque ripples. A new Open-Source software called Pyleecan is used to analyze the motor characteristics, design and optimize the motor in view of output constraints such as maximum torque and minimum torque ripples. This paper investigates the tradeoffs between objectives of maximizing torque and minimizing torque ripples, ensuring that the 'best possible' physical motor parameters are selected through optimization. The paper ends with a discussion of the advantages and disadvantages of the optimized designs, along with the effect of different magnet grades.

This work adopted the Tesla Model 3 motor [12] as a baseline design which is a light duty passengers' vehicle and employs NSGA-II optimization to investigate the trade-offs between two different objective functions of maximizing torque and minimizing torque ripples. Additionally, the impact of different magnet grades on output performances are analyzed.

## 2 Methodology

The electromagnetic model of the IPM motor is described at the beginning of this section. After that, the model using Pyleecan software [13] is outlined. The verification of electromagnetic model using Motor-CAD software [14] comes after that. Next, the optimization process, use of different magnet grades and sensitivity analysis are described.

## 2.1 Electromagnetic Model

The analytical model of Interior Permanent Magnet motor is modelled in the steady state. MATLAB [21] is used for the analytical model based on a 54 slot 6 pole IPM motor from the Tesla Model 3 and verified using two different software Pyleecan and Motor-CAD. The magnetic properties of the chosen magnet materials are provided in [15]. The Magnets are “V shaped”. Table 1 gives the initial motor specifications for the baseline design.

**Table 1.** Initial motor specifications

| | |
|---|---|
| Number of pole pairs | 6 |
| Stator outer diameter (mm) | 232.1 |
| Stator inner diameter (mm) | 151.5 |
| Rotor outer diameter (mm) | 148 |
| Rotor inner diameter (mm) | 70 |
| Stack length (mm) | 135 |
| Airgap (mm) | 0.85 |
| Number of Slot | 54 |
| Magnet material | N40 UH |
| Rated RMS current (A) | 800 |
| Rated Speed (RPM) | 17900 |

The steady state voltage equations for d and q axes of an IPMSM are presented by Eqs. (1) and (2) [16].

$$v_q = R_s i_q + w_e \lambda_m + w_e L_d i_d \tag{1}$$

$$v_d = R_s i_d - w_e L_q i_q \tag{2}$$

where $v_q$, $v_d$, $i_q$, $i_d$ are $q$ and $d$ axis voltages and currents, $L_q$, $L_d$ are $q$ and $d$ axis inductances, $Rs$ shows phase resistance, $\omega_e$ is electrical frequency and $\lambda_m$ is permanent magnet flux linkage. The electromagnetic torque developed for an IPM motor can also be found as, [16]

$$T_{em} = \frac{3p}{2}\left[\lambda_m i_q + \left(L_d - L_q\right)\right] i_d i_q \tag{3}$$

where, $p$ is the number of pole pairs.

## 2.2 Pyleecan Model

A Python-based open-source software Pyleecan (PYthon Library for Electrical Engineering Computational ANalysis) [13] is used to verify the analytical design. The software includes object-oriented modelling of 2D machines and multi-objective optimization [17]. In this study, the Graphical User Interface of this software is used to model the IPM motor, where the design parameters of the machine are defined in their respective sections. The electromagnetic model of the motor is then simulated using the magnetic and electrical modules in the software is used to simulate and observe the output performance of the machine. The Pyleecan model of the IPM motor is shown in Fig. 1.

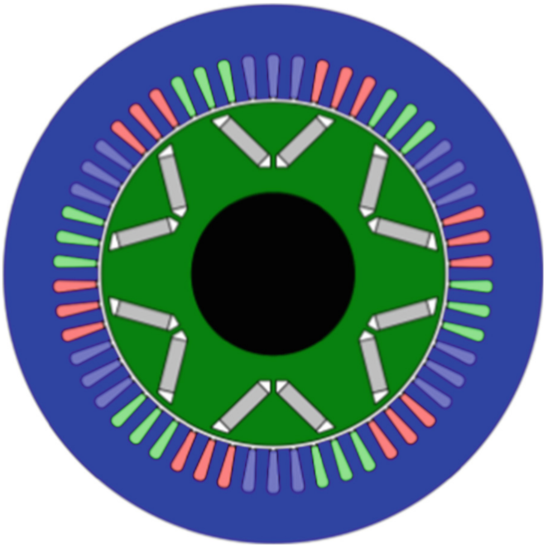


**Fig. 1.** IPM motor design in Pyleecan

The air gap flux density of the Pyleecan model differs by only 3% from the analytical design, which gives good validity of the model.

The overall torque of the above simulated motor is 402 Nm and the power is 167 kW. The output of the above simulated motor is given in Fig. 2. It can be observed that there is a high fluctuation in torque of 30.57 Nm, which is the peak-to-peak value of the torque ripples.

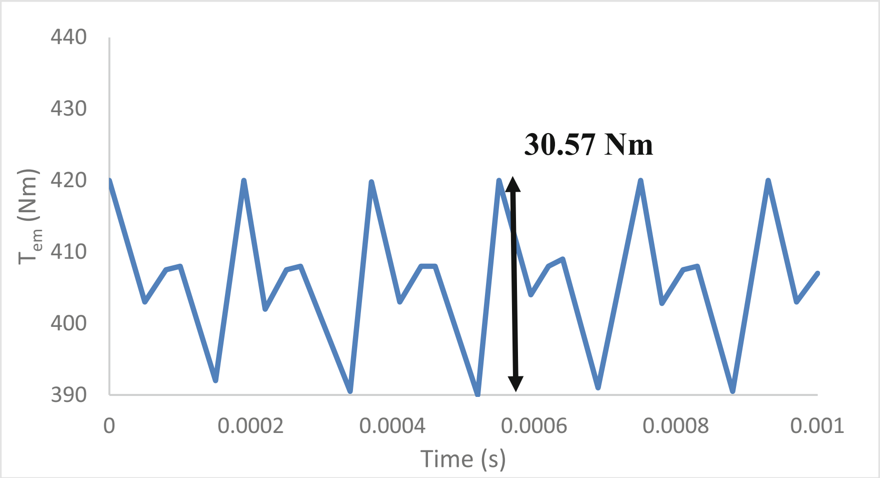



**Fig. 2.** Motor output with torque ripples

### 2.3 Motor-CAD Model

The electromagnetic model of the IPM motor again verified using Motor-CAD software [14] to observe the performance of the comparatively new open-source software Pyleecan. Figure 3 shows the developed electromagnetic model using Motor-CAD.

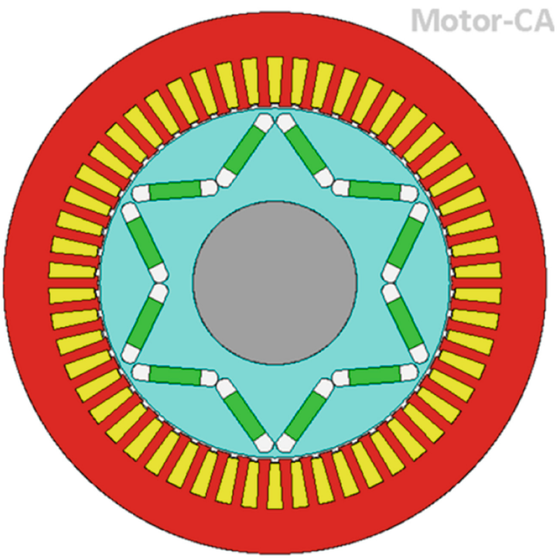



**Fig. 3.** IPM motor design in Motor-CAD

Output results of Motor-CAD model shows good validity of Pyleecan model. Figure 4 gives the Torque Speed characteristics of the IPM motor for different model.

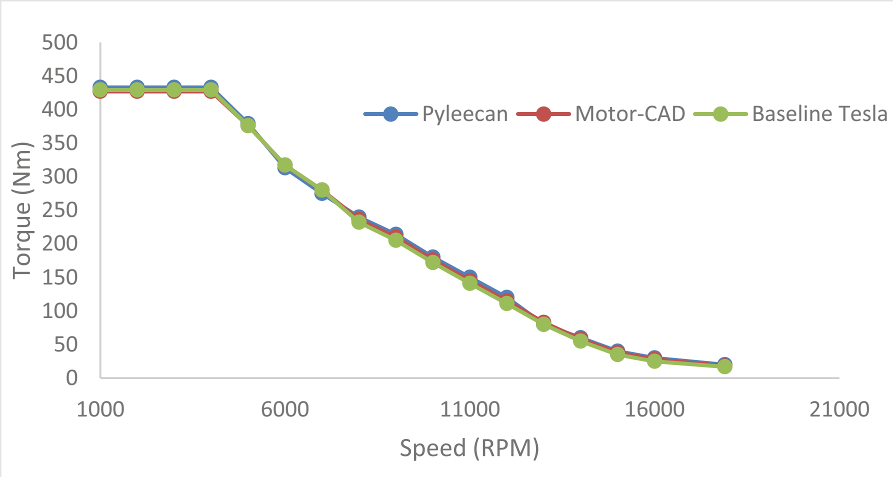



**Fig. 4.** Torque Speed characteristics of the IPM motor for Baseline Tesla, Pyleecan and Motor-CAD model

## 2.4 Optimization

To optimize the IPM motor, the Pyleecan software [13] is used. This software utilizes one of the most efficient algorithms in the realm of multi-objective optimizations, the NSGA-II algorithm [18]. In this study, it is particularly suitable due to its speed and accuracy. A random initial population is generated in this optimization method and the goal is to narrow down designs that meet the objective of the optimization and rank them. From the population, the offsprings are generated through selection, crossover, and mutation. This process repeats until the algorithm terminates [19].

To maximize the torque and minimize the torque ripple, optimal designs can be given as [20]

$$Design\ A = maxF_1(x) \tag{4}$$

$$Design\ B = minF_2(x) \tag{5}$$

where $x$ boundary limits and constraints for the optimization.

In this study, magnet height, magnet width, stator teeth height, number of pole pair, and stator diameter is chosen as independent variables for the optimization. The size of population is set as 52 and the number of generations as 8. Table 2 shows the lower boundaries (LB) and the upper boundaries (UB) for the independent variables.

**Table 2.** Boundary limits for the independent variables

| Independent variables | LB | UB |
|---|---|---|
| Number of pole pairs | 6 | 8 |
| Stator teeth height (mm) | 15 | 30 |
| Stator outer diameter (mm) | 115 | 120 |
| Magnet length (mm) | 15 | 25 |
| Magnet width (mm) | 4 | 8.5 |

### 2.5 Different Magnet Grades

The output performances were analyzed by replacing baseline magnet grade N40UH with different magnet grades of same temperature range. Different magnet grades are used to see the effect on motor performances for the same amount of magnet. Table 3 shows different Neodymium magnet grades that were used for this analysis.

**Table 3.** Different magnet grades [15]

| Magnet grade | Remanent flux density(T) |
|---|---|
| N30UH | 1.13 |
| N35UH | 1.21 |
| N40UH | 1.29 |
| N42UH | 1.31 |

## 3 Results and Discussions

Table 4 gives the results of the optimization process for optimal design A (maximum torque) and B (minimum torque ripple). Design A gives a small reduction in torque ripples and an increase in torque and power by increasing magnet width, stator diameter, teeth height and reducing magnet length while maintaining the number of pole pair. Whereas, design B has increased pole number, stator diameter, teeth height and reduced magnet length while magnet width is maintained.

**Table 4.** Optimization results

| | Baseline | Design A | Design B |
|---|---|---|---|
| Number of pole pairs | 6 | 6 | 8 |
| Stator teeth height (mm) | 18.8 | 19.2 | 22 |
| Stator outer diameter (mm) | 116.05 | 117 | 120 |
| Magnet length (mm) | 25 | 24 | 22 |
| Magnet width (mm) | 7 | 8 | 7 |
| Torque (Nm) | 402 | 417 | 380 |
| Torque Ripples (Nm) | 30.57 | 20.74 | 6.88 |
| Power (kW) | 167 | 173 | 148 |

Design B significantly reduced torque ripples, but it is accompanied by a small reduction in torque and power.

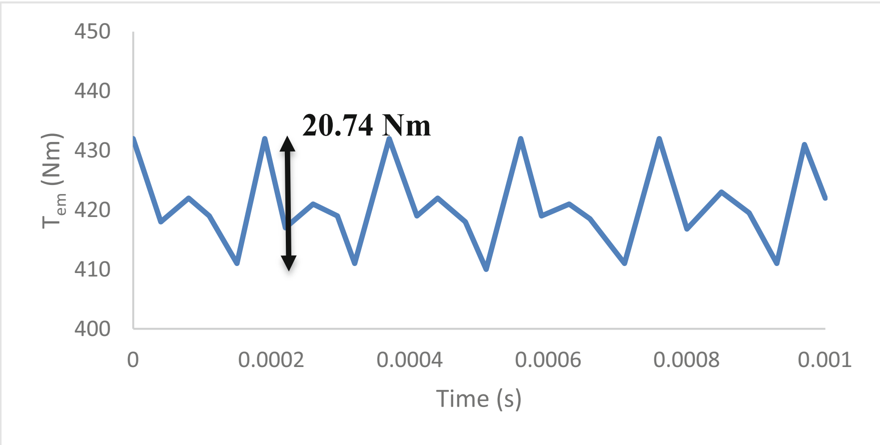



**Fig. 5.** Torque and torque ripple of Design A

Figure 5 and Fig. 6 shows the torque ripple of design A and design B. Table 5 illustrates that, for same amount of magnet, replacing the magnet grade increase torque and power with increasing magnet grade.

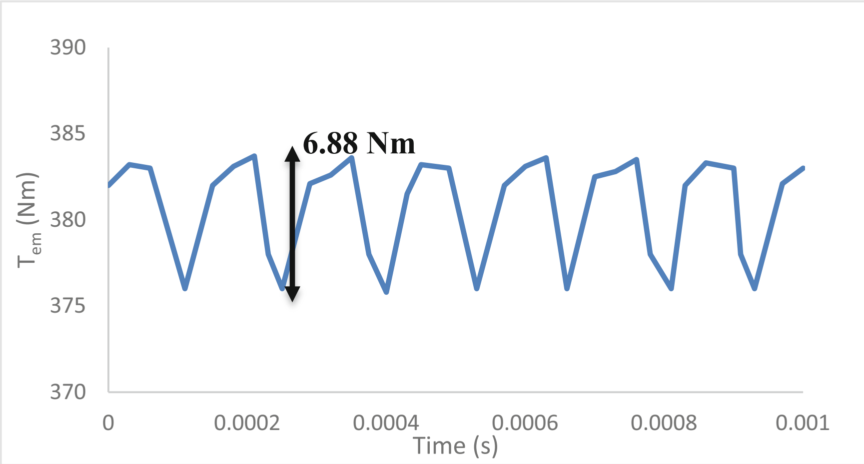



**Fig. 6.** Torque and torque ripples of Design B

**Table 5.** Effect of different magnet grades

| Magnet Grade | Design A | | Design B | |
|---|---|---|---|---|
| | Torque (Nm) | Power (kW) | Torque (Nm) | Power (kW) |
| N30UH | 381 | 152 | 341 | 126 |
| N35UH | 390 | 158 | 354 | 134 |
| N40UH | 417 | 173 | 380 | 148 |
| N42UH | 425 | 175 | 389 | 154 |

## 4 Conclusion

This paper optimized IPM motor for electric vehicle and explored the effects on sustainable transportation. This paper presented the issue of cogging torque and its effect on the performance of interior permanent magnet motors. The optimization yielded two designs whose performances are compared in terms of the overall torque, torque ripples, and power. This demonstrated that the design B with increased pole number, stator diameter, teeth height, and reduced magnet length had a superior performance in terms of torque ripples, which is reduced by 77% compared to that of the initial design. Furthermore, analysis was extended to the performance of designs based on different magnet grades and their respective results were compared. It can be seen that for the same amount of magnet, replacing the magnet grade increase torque and power with increasing magnet grades. It is also shown that optimization of EV motor to maximize torque and to minimize torque ripples can improve the performance of EV which can play an important role to fulfil the requirements of sustainable transportation. Further research can be performed on cost of energy and different motor topologies to see the effect on EV.

## References

1. Abdelmoula, R., Hadj, N.B., Chaieb, M., Neji, R.: Reducing torque ripples in permanent magnet synchronous motor. J. Electr. Syst. **13**(3), 528–542 (2017)
2. Sheela, A., Atshaya, M.: Design of permanent magnet synchronous motor for electric vehicle application using finite element analysis. Int. J. Sci. Technol. Res. **9**, 523–527 (2020)
3. Dalcali, A., Kurt, E., Çelik, E., Öztürk, N.: Cogging torque minimization using skewed and separated magnet geometries. Politeknik Dergisi **23**, 223–230 (2020)
4. Xu, P., Shi, K., Sun, Y., Zhua, H.: Effect of pole number and slot number on performance of dual rotor permanent magnet wind power generator using ferrite magnets. AIP Adv. **7**(5), 056631 (2017)
5. Xu, Q., Sun, J., Wang, W., Mao, Y., Cui, S.: Design optimization of an electric variable transmission for hybrid electric vehicles. Energies **11**(5), 1118 (2018)
6. Chaieb, M., Tounsi, S., Neji, R., Sellami, F.: Optimum geometry for torque ripple minimization of permanent magnet motor by the finite element method. In: MELECON 2008 – The 14th IEEE Mediterranean Electrotechnical Conference, pp. 459–464 (2008)
7. Zhu, Z.Q., Howe, D.: Influence of design parameters on cogging torque in permanent magnet machines. IEEE Trans. Energy Convers. **15**(4), 407–412 (2000)
8. Hwang, M.H., Lee, H.S., Cha, H.R.: Analysis of torque ripple and cogging torque reduction in electric vehicle traction platform applying rotor notched design. Energies **11**(11), 3053 (2018)
9. Aydin, E., Li, Y., Aydin, I., Aydemir, M.T., Sarlioglu, B.: Minimization of torque ripples of interior permanent magnet synchronous motors by particle swarm optimization technique. In: 2015 IEEE Transportation Electrification Conference and Expo (ITEC), pp.1–6. IEEE (2015)
10. Chu, W.Q., Zhu, Z.Q.: Investigation of torque ripples in permanent magnet synchronous machines with skewing. IEEE Trans. Magn. **49**(3), 1211–1220 (2012)
11. Constantin, A.I., Dumitru, C., Tudor, E., Vasile, I., Arsene, M.: Studies related to the optimization of an interior permanent magnet synchronous machine designed for the electric vehicles. In: 2021 International Conference on Applied and Theoretical Electricity (ICATE), pp. 1–5. IEEE (2021)
12. Estore.ricardo.com. 2021. Ricardo Tesla Model 3 2018 motor analysis with winding diagram – Ricardo eStore. https://estore.ricardo.com/en/2018-tesla-model-3-motor-reportwith-winding-analysis-c-23-c-70-p-481
13. Pyleecan: https://www.pyleecan.org/ (2021)
14. Motor-CAD Software: https://www.motor-design.com/motor-cad/ (2021)
15. Neodymium Iron Boron Magnets: Arnold Magnetic Technologies, Rochester, NY, USA. http://www.arnoldmagnetics.com/en-us/Products/Neodymium-Magnets (2022). Accessed 24 Mar 2022
16. Toulabi, M.S., Salmon, J., Knight, A.M.: Concentrated winding IPMsynchronous motor design for wide field weakening applications. IEEE Trans. Ind. Appl. **53**(3), 1892–1900 (2017)
17. Bonneel, P., Le Besnerais, J., Pile, R., Devillers, E.: Pyleecan: an open-source Python object-oriented software for the multiphysic design optimization of electrical machines. In: 2018 XIII International Conference on Electrical Machines (ICEM), pp. 948–954. IEEE (2018)
18. Deb, K., Pratap, A., Agarwal, S., Meyarivan, T.A.M.T.: A fast and elitist mul-tiobjective genetic algorithm: NSGA-II. IEEE Trans. Evol. Comput. **6**(2), 182–197 (2002)
19. Benlamine, R., Dubas, F., Randi, S.A., Lhotellier, D., Espanet, C.: Design by optimization of an axial-flux permanent-magnet synchronous motor using genetic algorithms. In: 2013 International Conference on Electrical Machines and Systems (ICEMS), pp. 13–17. IEEE (2013)

20. Le Besnerais, J., Lanfranchi, V., Hecquet, M., Brochet, P.: Multiobjective optimization of induction machines including mixed variables and noise minimization. IEEE Trans. Magn. **44**(6), 1102–1105 (2008)
21. MATLAB R2018b: https://www.mathworks.com/products/matlab.html (2018)

# Broader Impacts of Implementing Industrial Energy-Efficient Lighting Assessment Recommendations

Phillip Shook[1] and Jun-Ki Choi[2](✉)

[1] Ameresco, 8825 Stanford Blvd, Columbia, MD 21045, United States
[2] Department of Mechanical Engineering, University of Dayton, Dayton, OH 45409, U.S.A.
jchoi1@udayton.edu

**Abstract.** This article evaluates the economic and environmental impact that small- and medium-size industries' investments in energy-efficient lighting improvements had on a Midwest region in the U.S. Utility rebate programs were also examined to identify the importance that these programs can have in encouraging industries to invest in energy efficiency, which was shown to positively benefit multiple economic sectors. An economic input-output analysis is used to estimate the cascading regional economic impacts of implementing the energy-efficient lighting upgrades in manufacturing facilities. It was found that if lighting recommendations were implemented throughout all manufacturers in the study region, implementation costs through rebate programs could be decreased by €64M, and about €435M could be directly invested into the economy, which could save about €265M in energy costs and 2.9 million tonnes of $CO_2$ emissions.

**Keywords:** Industrial energy efficiency · Industrial energy audit · Input-output analysis · Lighting

## 1 Introduction

According to the United States Energy Information Administration, the industrial sectors consume about 35% of U.S end-use energy consumption and about 32% of total U.S energy consumption. About 12% of the consumption is from electricity, which produces about 25% of greenhouse gases in the U.S [1]. Researchers have shown that increases in greenhouse gas emissions have led to a global temperature increase by about 0.5–1 °C over the last 100 years [2]. European Union (EU) has established different plans and directives that regulate the efficiency of different energy systems in buildings [3]. Schweiger et al. [4] concluded that consumer participation greatly influences the efficacy of smart energy systems and can reduce energy demand. Energy audits have been shown to influence small to medium-sized manufacturers (SMEs) to invest in energy-efficient practices to influence more participation [5]. The U.S Department of Energy sponsors multiple Industrial Assessment Centers (IACs) nationwide that perform no-cost energy assessments that typically identify about €130,000 of potential energy-saving opportunities for SMEs [6–8]. Lighting is the most prominent energy system IAC teams notice


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 312–321, 2023.
https://doi.org/10.1007/978-981-19-9205-6_30

when they begin an assessment because light fixtures are placed in nearly all areas of facilities since they are necessary for people's productivity and health [9]. According to 2014 data, lighting in manufacturing facilities consumed about 1.4% of total U.S electricity consumption [10]. Thus, increasing the efficiency of lights or reducing the usage of artificial lights can reduce peak electricity loads, the burning of fossil fuels, and greenhouse gases released into the environment. This article analyzes the economic and environmental effects generated by energy efficient lighting recommendations that the University of Dayton's Industrial Assessment Center (UD-IAC) offered to the manufacturing facilities across Ohio between 2008 and 2018. This article also analyzes the effect of energy efficient lighting rebates have had on encouraging manufacturers to implement lighting recommendations.

## 2 Literature Reviews

Advancements in lighting technology have made lighting more efficient, and with rebate opportunities provided by some utility companies, facilities have more incentive to upgrade their outdated systems. Studies have highlighted the benefits of different energy-efficient lighting retrofits in reducing energy usage and greenhouse emissions. Multiple researchers found that commercial office buildings could reduce their electricity consumption by retrofitting wireless sensors for occupancy lighting control. Controlling lighting can be difficult if different users require different comfort levels [11]. Papatsima and Linnartz developed a layered architecture model for building control that could keep user comfort and create 30% energy savings [12]. Installing lighting controls usually require a capital investment. However, due to increases in energy efficiency programs, more than 70% of the U.S has lighting rebate programs covering lighting systems, including lighting controls [13]. As energy efficiency has become more important, a key issue has been to replace old, inefficient light bulbs with light emitting diode (LED) bulbs. According to researchers, about 95% of lights in Brazil were incandescent before 2001 [14]. Replacing these lamps with LEDs has many benefits, including increased efficiency, decreased replacement costs, and a lower life-cycle impact [15]. The color temperature of LED lamps can also impact the thermal comfort of occupants, which can also reduce heating and cooling loads, thus reducing energy usage and costs. Due to these benefits, LEDs are typically included in energy efficiency rebate programs across the U.S. [16]. For example, Ohio passed a bill in 2008 that set a standard of energy reduction by 23% by 2027. To help achieve this goal, many utility companies in the state have offered rebates to residential, commercial, and industrial clients to switch to energy-efficient lighting. While artificial lighting has come a long way to become more efficient, another effective method to reduce energy usage is to utilize natural lighting instead of artificial. Daylight has many benefits to buildings and the occupants inside, including increasing the mood of the occupants as well as reducing cooling loads and energy demand [17]. Utilizing both artificial and natural lighting can provide occupants with a good balance of visibility and comfort. A study performed by Sun et al. [18] found that incorporating smart windows made of a transparent insulation material that automatically regulates natural light, and solar heat can have about 27% energy savings compared to standard windows. When making recommendations to utilize daylight, it is important to consider the function and orientation of the room because some tasks cannot be performed properly with just daylight as the main source of visibility [18]. Many economic models are available for analyzing the various macroeconomic impacts of technologies [19–21], policy implications [22], energy efficiencies [23], etc. Both general equilibrium and partial equilibrium models have been used for energy economics analysis. Out of many different general equilibrium models, economic input-output (EIO) analysis has adopted by most countries in the world for their national accounting methods. Many different techniques are available for the EIO analysis [24, 25]. One popular way of using the EIO is to analyze the impact of the changes in value-added (i.e., tax, subsidy, employment, and investment) on the whole economy [26–28].

## 3 Methodology

Figure 1 illustrate the overall framework of this study. Data from energy assessments performed by the UD-IAC between the years 2008 and 2018 was gathered to estimate the overall economic and environmental impact that the UD-IAC team had on the state of Ohio. During an assessment, the team analyzes different energy systems' performance across facilities and presents findings for potential energy-saving recommendations. Along with energy savings, these recommendations can save facilities money and reduce their $CO_2$ emissions. After an assessment is completed, a survey is sent out nine months later to understand which recommendations were most helpful and were implemented. This study focuses on recommendations for lighting systems out of the many different energy systems analyzed during assessments. Recommendations usually require a capital cost, which can deter facilities from implementing them, but this cost can benefit the community because money can flow through the economy and stimulate business. Rebate programs offered by utility companies were applied to some of the recommendations, reducing the total implementation cost. To get a broad view of all the economic sectors impacted, all implementation costs were divided into labor and material costs. The total amount of applied rebates were also considered to understand their impact on saving facilities' implementation costs. Economic Input-Output analysis [29] was utilized to investigate the cascading economic impact of the industrial energy efficient lighting investment. The implementation costs were allocated to different North American Industry Classification System (NAICS) sectors. The sectors directly impacted by energy-efficient lighting system recommendations are identified. Those direct impacts also have the potential for increasing production in other upstream industries in the supply chain, which are categorized as indirect effects. Both these direct and indirect effects also increase the income of the employees of all of these industries, which can then be spent on local services, education, healthcare, etc. These effects on the broader community are considered induced effects. We determined value not only from an economic outlook but from an environmental one. Three scenarios were created and analyzed to estimate the economic and environmental effects. The first scenario estimates the effects generated by the 139 lighting recommendations that facilities implemented. The second scenario focuses on the 222 recommendations offered but not implemented. The final scenario looked at the effects of all the recommendations and extrapolated estimates for all manufacturing facilities in Ohio. While there were already some policy and rebate programs offered when these recommendations were made, these analyses offer a perspective on adopting a stronger energy efficiency policy in government.

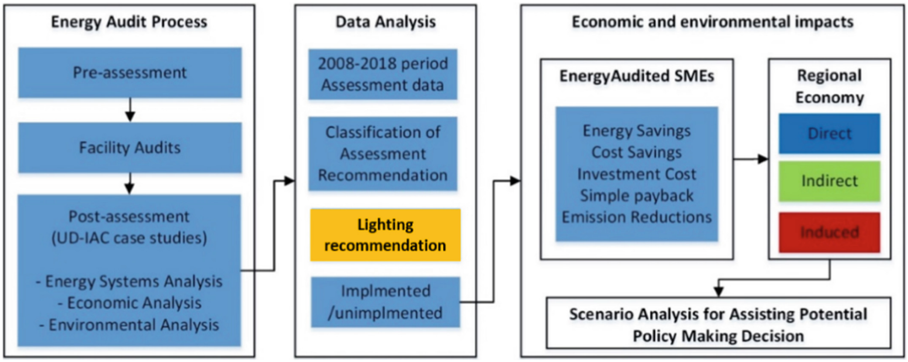



**Fig. 1.** Overall framework for analyzing impacts of lighting implementations

## 4 Energy-Efficient Lighting Recommendations

Table 1 lists the different types of assessment recommendations (ARs) and the category where each recommendation belongs. Since this work aims to analyze the broader economic impacts of implementing the energy-efficient lighting system, it is not the scope of this article that presents the technical calculation of these ARs. All the technical analyses of the energy-efficient AR examples are available in the UD-IAC resources [30]. The data from these recommendations are used in the input-output analyses section further in this article.

## 5 Regional Economic and Environmental Impacts of Lighting Implementation

This section examines the effects of implementing energy-efficient lighting recommendations in industrial facilities on different economic sectors in Ohio. This section also looks at the role that rebates played in encouraging facilities to implement recommendations and how much the rebates reduced the implementation costs. The implementation cost includes the cost of materials, equipment, and labor needed which creates direct, indirect, and induced effects that benefit other manufacturers, suppliers, consulting services, and other sectors. These sectors are all affected by the environmental impact that these recommendations generate. This analysis covers the lighting recommendations recommended to 171 facilities in Ohio between 2008 and 2018. Table 2 shows the estimated annual cost savings, the implementation costs, and the average payback period for the recommendations of each category. Implementation costs include the material, labor, and any cost associated with offered rebates. This analysis shows that implementing

**Table 1.** Breakdown of recommendations for increasing the efficiency of lighting systems

| Category | Description of the assessment recommendation |
|---|---|
| Controls | Install occupancy sensors |
| | Add area lighting switches |
| | Install timers on light switches in little used areas |
| | Use separate switches on perimeter lighting, which may be turned off when natural light is available |
| | Use photocell controls |
| Hardware | Utilize higher efficiency lamps and ballasts |
| | Install skylights |
| | Lower light fixtures in high ceiling areas |
| | Install spectral reflectors/delamp |
| Operation | Utilize daylight whenever possible in lieu of artificial light |
| | Make a practice of turning off lights when not needed |
| | Keep lamps and reflectors clean |
| | Disconnect ballasts |
| Levels | Reduce illumination to minimum necessary levels |

energy-efficient lighting recommendations can provide facilities with short-term simple payback periods. Three of the four categories observed had average simple paybacks of less than six months. Lighting hardware recommendations had an average payback of over two years. The higher simple payback of lighting hardware recommendations can be attributed to the fact that they were the most implemented recommendation. Along with being recommended the most, hardware recommendations include retrofitting light-bulbs to higher-efficiency bulbs, which typically have high implementation costs due to the high number of bulbs that need to be retrofitted at one time. The implementation costs were broken down into material and labor costs, and Table 3 displays the different NAICS sectors to which those costs were allocated.

**Table 2.** Labor, material, and rebate costs for implemented assessment recommendations

| Category | Savings | Labor costs | Material costs | Rebate costs | Payback (month) |
|---|---|---|---|---|---|
| Controls | €161,465 | €32,888 | €53,985 | €25,480 | 5 |
| Hardware | €1,173,004 | €379,977 | €2,358,561 | €383,026 | 25 |
| Operation | €165,382 | €10,615 | €12,032 | 2,455 | 2 |
| Levels | €2,770 | €0 | €0 | €0 | 0 |

**Table 3.** Allocation of total implementation costs to the NAICS sector

| NAICS | Description | Allocated cost |
|---|---|---|
| 335110 | Bulbs, electric light, complete, manufacturing | €1,133,406 |
| 333413 | Light emitting diodes (LED) manufacturing | €839,554 |
| 238210 | Electrical contractors and other wiring installation contractors | €420,600 |
| 334290 | Motion detectors, security system, manufacturing | €34,625 |
| 332321 | Skylights, metal, manufacturing | €3,282 |
| 238350 | Window installation | €2,880 |
| 335129 | Reflectors for lighting equipment, metal, manufacturing | €2,575 |
| 335931 | Switches for electrical wiring (e.g., pressure, pushbutton, snap, tumbler) manufacturing | €175 |

The result of the input-output analysis allowed us to identify all of the economic sectors affected by the implemented lighting recommendations. In total, 505 different sectors had some economic benefit. Figure 2 shows a selection of 20 of those identified sectors to show the variance and percentage of direct, indirect, and induced effects across a wide range of economic sectors. Looking at the directly impacted sectors, four out of the five sectors manufacture equipment and materials required to complete a recommendation. The fifth sector includes services facilities that would need to consult and hire to perform the labor necessary to implement recommendations. The indirectly affected sectors include those businesses that interact with the directly impacted sectors. For instance, wholesalers of machinery and equipment are positively impacted when the equipment manufacturers increase production. It is interesting to note that the sector of insurance agencies, brokerages, and related activities had a higher indirect impact. The sectors affected the most by induced effects include hospitals, dentists, and physician offices. The increased income by the directly and indirectly affected sectors allowed for more spending on health and wellness.

Along with material and labor costs, some recommendations can utilize rebates offered by utility companies to lower the total implementation cost. Figure 3 compares the percentage of recommendations utilizing rebates to how much those rebates were able to reduce the implementation costs of the recommendations. This analysis shows that offering rebates can play a role in reducing implementation costs for energy-efficient lighting recommendations. For instance, facilities audited in 2011 were able to save almost 16 times more than those audited in 2009 because of the much larger percentage of recommendations that could utilize rebates. It is interesting that 2011 saw a lower percentage of rebates being utilized but saw higher savings than 2010. Since most rebates provide savings per retrofit, UD-IAC provided facilities in 2011 with recommendations that required more lighting retrofits than the recommendations offered in 2010. When comparing all of the years that utilized some number of rebates, the years that rebates were a part of 50% or more of the recommendations, facilities saved about twice as much as the facilities in the years where rebates made up less than 50%.

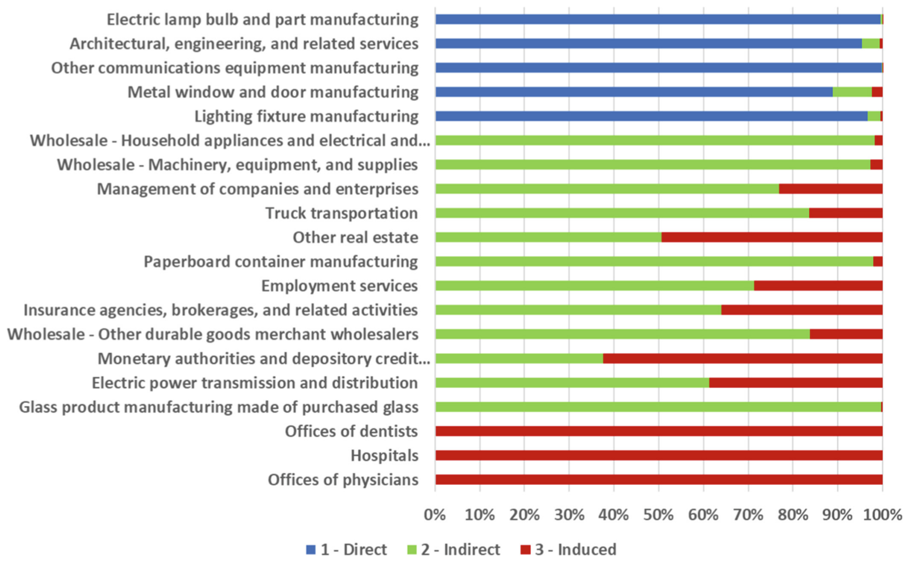



**Fig. 2.** Twenty selected economic sectors affected by the implementation of energy-efficient lighting recommendations, with estimated percentages of direct, indirect, and induced benefits

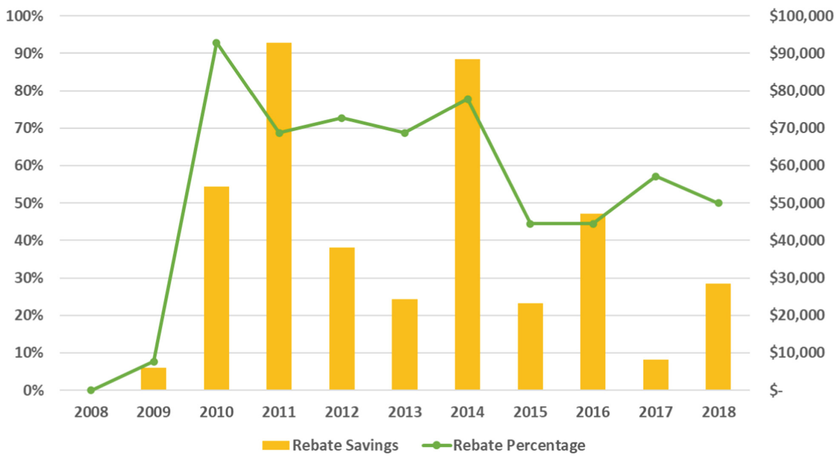



**Fig. 3.** Comparison of the percentage of recommendations with rebates and the impact on the capital cost

Figure 4 compares the economic and environmental impact of three scenarios involving energy-efficient lighting system recommendations. After estimating the total economic output (i.e., direct, indirect, induced) by the EIO model, emission intensity factors for all economic sectors are multiplied to estimate the avoided $CO_2$. The first scenario compares the impact of the 139 lighting recommendations that facilities implemented. Similarly, the second scenario focuses on the 222 lighting recommendations offered but not implemented by facilities. The third scenario estimates the impact if facilities had implemented all of the offered recommendations. In the first scenario, facilities invested about €2.5M, which allowed them to save about €1.5M annually and 16,000 tonnes of $CO_2$. Almost 1.5 times more recommendations were made in the second scenario than in the first scenario, which affected implementation cost, energy savings, and carbon emission reduction by 1.5. The recommendations included in the second scenario could save facilities about €3.5M per year and reduce their annual carbon emissions by about 23,000 tonnes. When looking at scenario 3, facilities had the potential to reduce their annual emissions by about 40,000 tonnes and annually save about €3.6M. However, this would have cost them about €6M. This analysis showed that the greater number of lighting recommendations that facilities implement, annual energy costs can decrease, and carbon emissions will decrease while maintaining a simple payback. Facilities can take advantage of generating more savings by implementing more energy-efficient lighting recommendations if the simile payback can remain constant.

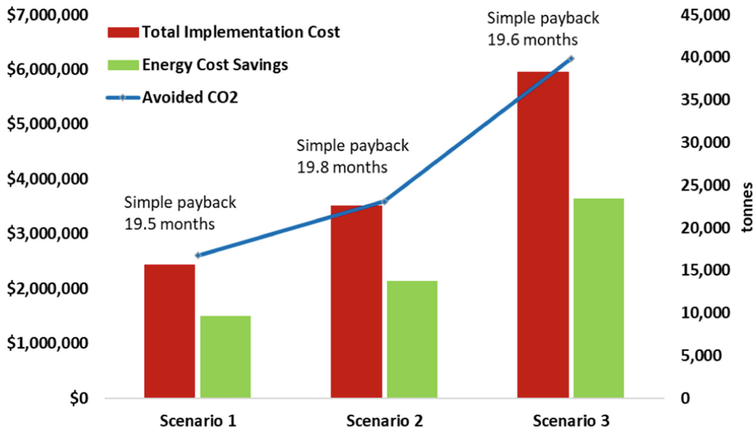



**Fig. 4.** Comparison of economic and environmental impacts of three scenarios considered

Extrapolating the data from the previous analysis, estimations were made for the potential impact that all Ohio manufacturers could have on the economy and environment if similar energy-efficient lighting recommendations were implemented. According to 2017 and 2019 data, 12,371 manufacturing facilities in Ohio added about €112 billion to the economy and about 37.6 million metric tonnes of $CO_2$ into the atmosphere [31, 32]. Suppose every Ohio manufacturer implemented energy-efficient lighting practices similar to the recommendations offered to manufacturers during UD-IAC audits. In that case, Ohio manufacturers could annually save €265M in energy costs and about 2.9 million tonnes of $CO_2$. This would be about a 7% reduction in annual $CO_2$ emissions. It was estimated that these savings would come at about €435M, but rebate programs would allow savings of about €64M.

## 6 Conclusion

This article looks at how a small portion of Ohio manufacturers during ten years was able to impact the economy and environment of Ohio through implementing energy-efficient lighting practices after being offered by UD-IAC. This article also analyzes the impact that rebate programs have had on those practices. A wide variety of economic sectors can be impacted through direct, indirect, and induced effects by the various lighting recommendations that UD-IAC offers to facilities. Any amount of investment was able to have an impact on the facility itself as well as the community. Rebate programs played an important role in convincing facilities to implement certain recommendations due to the cost savings they can create. Even though rebates save money that would have gone into the economy, the rebates help generate more interest in recommendations that can add even more money to the economy. Including rebates, the assessed facilities directly invested about €2.5M, which added another €2.5M to the economy through indirect and induced effects.

In 2019, Ohio enacted House Bill 6, which minimized Ohio's renewable-energy goals and brought an end to energy efficiency rebates offered by Ohio utility companies [34]. However, utility companies can still offer rebates if they get permission. This article can be used as evidence of the impact that rebate programs have had on incentivizing manufacturers to implement energy-efficient recommendations that save them money and stimulate the economy and reduce carbon emissions released into the atmosphere. This article showed that manufacturers tended to see higher savings when more rebates were taken advantage of, which created a lower return on investments and more incentive to become more energy efficient.

## References


1. United States Enviornmental Protection Agency: Greenhouse gas emissions (2021)
2. Mikhaylov, A., Moiseev, N., Aleshin, K., Burkhardt, T.: Global climate change and greenhouse effect. Entrepreneurship and Sustainability Issues **7**(4), 2897–2913 (2020)
3. Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., Castellazzi, L.: Review of 50 years of EU energy efficiency policies for buildings. Energy Build. **225**, 110322 (2020)
4. Schweiger, G., et al.: Active consumer participation in smart energy systems. Energy Build. **227**, 110359 (2020)
5. Kalantzis, F., Revoltella, D.: Do energy audits help SMEs to realize energy-efficiency opportunities? Energy Econ. **83**, 229–239 (2019)
6. Industrial Assessment Center: U.S. Department of Energy. Advanced Manufacturing Office (2022)
7. Choi, J.-K., Schuessler, R., Ising, M., Kelley, D., Kissock, K.: A pathway towards sustainable manufacturing for mid-size manufacturers. Procedia CIRP **69**, 230–235 (2018)
8. Choi, J.-K., Thangamani, D., Kissock, K.: A systematic methodology for improving resource efficiency in small and medium-sized enterprises. Resour. Conserv. Recycl. **147**, 19–27 (2019)
9. Boyce, P.R.: Review: the impact of light in buildings on human health. Indoor Built Environ. **19**(1), 8–20 (2010)
10. United States Energy Information Administration: How much electricity is used for lighting in the United States? (2021)

11. Peruffo, A., Pandharipande, A., Caicedo, D., Schenato, L.: Lighting control with distributed wireless sensing and actuation for daylight and occupancy adaptation. Energy Build. **97**, 13–20 (2015)
12. Papatsimpa, C., Linnartz, J.P.M.G.: Propagating sensor uncertainty to better infer office occupancy in smart building control. Energy Build. **179**, 73–82 (2018)
13. DiLouie, C.: Advanced Lighting Controls: Energy Savings, Productivity, Technology and Applications. Fairmont Press (2014). https://doi.org/10.1201/9781498710350
14. Theodoro, T., et al.: 60 W incandescent lamp alternatives found in brazilian market (2014)
15. Huebner, G.M., Shipworth, D.T., Gauthier, S., Witzel, C., Raynham, P., Chan, W.: Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort. Energy Res. Soc. Sci. **15**, 45–57 (2016)
16. Choi, J.-K., Eom, J., McClory, E.: Economic and environmental impacts of local utility-delivered industrial energy-efficiency rebate programs. Energy Policy **123**, 289–298 (2018)
17. Bournas, I., Dubois, M.-C.: Residential electric lighting use during daytime: a field study in swedish multi-dwelling buildings. Build. Environ. **180**, 106977 (2020)
18. Sun, Y., et al.: Energy and daylight performance of a smart window: Window integrated with thermotropic parallel slat-transparent insulation material. Appl. Energy **293**, 116826 (2021)
19. Errigo, A., Choi, J.-K., Kissock, K.: Techno-economic-environmental impacts of industrial energy assessment: sustainable industrial motor systems of small and medium-sized enterprises. Sustainable Energy Technol. Assess. **49**, 101694 (2022)
20. McLaughlin, E., Choi, J.-K., Kissock, K.: Techno-economic impact assessments of energy efficiency improvements in the industrial combustion systems. J. Energy Resour. Technol. **144**(8), 1–22 (2021). https://doi.org/10.1115/1.4053137
21. Kapp, S., Choi, J.-K., Kissock, K.: Toward energy-efficient industrial thermal systems for regional manufacturing facilities. Energy Rep. **8**, 1377–1387 (2022)
22. Choi, J.-K., Friley, P., Alfstad, T.: Implications of energy policy on a product system's dynamic life-cycle environmental impact: survey and model. Renew. Sustain. Energy Rev. **16**(7), 4744–4752 (2012)
23. Choi, J.-K., Kissock, K., Hallinan, K., Brecha. R.: Economic and environmental impacts of energy efficiency investment on local manufacturers. In: ASME-IDETC, Boston, MA (2015)
24. Leontief, W.: Input–output analysis. In: The New Palgrave Dictionary of Economics, pp. 1–8. Palgrave Macmillan UK, London (2016). https://doi.org/10.1057/978-1-349-95121-5_1072-1
25. Leontief, W.W.: Quantitative input and output relations in the economic systems of the United States. Rev. Econ. Stat. **18**(3), 105–125 (1936)
26. Choi, J.-K., Bakshi, B.R., Hubacek, K., Nader, J.: A sequential input–output framework to analyze the economic and environmental implications of energy policies: Gas taxes and fuel subsidies. Appl. Energy **184**, 830–839 (2016)
27. Choi, J.-K., Bakshi, B.R., Haab, T.: Effects of a carbon price in the U.S. on economic sectors, resource use, and emissions: An input–output approach. Energy Policy **38**(7), 3527–3536 (2010). https://doi.org/10.1016/j.enpol.2010.02.029
28. Choi, J.-K., Morrison, D., Hallinan, K.P., Brecha, R.J.: Economic and environmental impacts of community-based residential building energy efficiency investment. Energy **78**, 877–886 (2014)
29. Miller, R.E., Blair, P.D.: Input-Output Analysis: Foundations and Extensions. Cambridge University Press (2009). https://doi.org/10.1017/CBO9780511626982
30. UD-IAC: University of dayton industrial assessment center. go.udayton.edu/iac (2022)
31. North America Manufacturers Association: 2021 ohio manufacturing facts (2021)
32. U.S. Energy Information Administration: Energy-related CO2 emission data tables (2017)

# A Preliminary Model for Delayed Product Differentiation Towards Mass Customization

Marco Bortolini(✉), Francesco Gabriele Galizia, and Ludovica Diletta Naldi

Department of Industrial Engineering, Alma Mater Studiorum - University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy

{marco.bortolini3,francesco.galizia3,ludovica.naldi2}@unibo.it

**Abstract.** In the recent years, the diversity in customer requirements asks industrial companies to move from mass production to mass customization, overcoming the traditional strategy of realizing a large volume of a single product in favor of the manufacturing of multiple product variants matching different customer needs. In such a scenario, traditional production strategies such as Make to Stock (MTS) and Make to Order (MTO) show some limitations, leading to the advent of new hybrid production strategies. The Delayed Product Differentiation (DPD) is one of the most relevant, which attempts to join the dual needs of high variety and quick customer response time by using the so-called product platforms. This working paper proposes a preliminary indicator to assess the similarity among a set of parts, i.e., product variants, according to their production cycle, acting as a first criterion to assess the feasibility of implementing the DPD strategy. The application of the proposed indicator to an operative industrial instance showcases its effectiveness to suggesting to the company whether to implement the DPD or to using traditional production strategies.

**Keywords:** Product variety · Mass customization · Delayed product differentiation · Product platforms

## 1 Introduction and Literature Review

The heterogeneity in customer needs is causing a wide proliferation of product variety, necessarily increasing the complexity in product planning and manufacturing [1]. Therefore, especially in Small & Medium Enterprises, most of the products derives from modules and components assembly. Hence, the variety magnitude propagates downwards across the different assembly levels of each variant [2]. Several factors exist affecting the increase in product variety. The most relevant is represented by the various customer's requirements, including functional features, or a desired level of performance, reliability, and serviceability [3]. A second factor affecting variety is represented by the different regional needs. In fact, some requirements differ from a region to another in terms of local preference, language, or govern regulations. Moreover, the presence of different market segments, rapid technology changeovers and price discrimination and competition are further elements affecting variety. In managing variety, the attributes of


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 322–330, 2023.
https://doi.org/10.1007/978-981-19-9205-6_31

similarity and commonality are crucial to reduce the complexity and the related costs. To this aim, the stream of Design for Variety (DfV) rose in the past years to join customers' needs and their relationship to families of technological solutions [4, 5]. Among the tools spread by DfV, the Quality Function Deployment (QFD) is a well-known tool supporting in identifying customers' requirements and their relationship to product specifications [6]. The study proposed by Rizzi and Regazzoni [7] explored the use of different design methodologies to manage product variety, such as the Module Interface Matrix, the Design Structure Matrix and the Pugh Matrix, applying them to a real product from the household appliance field. ElMaraghy and AlGeddawy [8] introduced an innovative method to design product variants integrating the similarity feature to the concept of co-evolution. Cladistics, i.e., an approach to biological classification in which organisms are categorized in groups ("clades") based on hypotheses of most recent common ancestry, was used to identify component modules. Then, algorithms are proposed for functional and structural analysis and for variants generation.

The analysis of current literature highlights that several strategies rose to manage product variety, acting both on the product structure, as the methods described above, and on the production strategies adopted to deliver them to the customers. In fact, in the current years governed by mass customization, traditional production strategies such as Make to Stock (MTS) and Make to Order (MTO) present limitations [9]. MTO leads to low warehouse costs but to high customer lead times, while MTS shows an opposite trend [10]. To best cope with the emerging trends, hybrid production strategies have been developed. The Delayed Product Differentiation (DPD) is among them and attempts to join the dual needs of high-variety and low customer lead times by using the so-called product platforms [11, 12]. Following the original definition, a product platform is "a set of sub-systems and interfaces forming a common structure from which a set of derivative variants can be produced" [13]. In detail, product platforms are manufactured and stocked following the MTS strategy in the first production stage. Then, they are reconfigured into different variants after the arrival of the customer order, following the MTO strategy, in the second production stage [11]. Among the most relevant studies available in current literature for product platform design, Ben-Arieh et al. [14] proposed an optimization model for platforms design to minimize their production cost determining the optimal number of platforms and their configuration. ElMaraghy and Abbas [15] developed a methodology for co-platforming to match the product features platform to the related manufacturing systems platform. Zhang et al. [16] introduced a method for platform planning using the product data available in the product lifecycle management (PLM) database. This method used the pruning analysis to find the most shared components within a set of product families, i.e., the platform, while the attribute matching methodology was used to classify the product modules into different categories according to their sharing degrees. Galizia et al. [12] proposed a decision support system for product platform design, selection, and customization in high-variety manufacturing by applying the median joining phylogenetic network methodology. Despite a set of models and methods for product platforms design is available in current literature, preliminary indicators assessing the feasibility and convenience of implementing the DPD strategy in industrial companies are missing. To fill this gap, this working paper proposes a preliminary indicator to assess the similarity among a set of parts, i.e., product variants, according to their production cycle, acting as a first criterion to evaluate the feasibility of implementing DPD. Unlike the existing similarity indicators, e.g., Jaccard similarity index, etc., the indicator proposed in this paper provides a global similarity measure by evaluating all the parts within the product mix towards the average length of the part production cycles.

Starting from this background, the remainder of this paper is structured as follows. Next Sect. 2 introduces and discusses the developed indicator, while its application to an operative industrial instance is in Sect. 3. Finally, Sect. 4 concludes this paper with final remarks and future research opportunities.

## 2 A Preliminary Indicator for Delayed Product Differentiation

The product platform concept is based on determining the shared components or operations among a set of parts, i.e., product variants. A low level of similarity in their production cycle may prevent the possibility to create common platforms and apply the DPD strategy in a successful way. For this reason, in this paper we propose a preliminary indicator to evaluate the parts similarity called Parts Similarity Index (PSI). According to the PSI values, the decision makers can decide whether to go on applying a specific product platforms design method or not, avoiding spending time and effort in unproductive further analysis. Positive feedbacks from this early part structure's study imply that the considered parts share a high level of operations, make them good candidates for the adoption of a DPD strategy.

To ensure a high level of applicability and ease of use, the structure of the indicator is kept simple using few basic assumptions on each part production cycle. In detail, as highlighted in next Fig. 1, the production cycle is made of a linear sequence of working operations, dealing with the assembly of specific components. An operation may involve more than one component and include components assembled also in other operations. In addition, each operation occupies a specific position, i.e., phase, in the production cycle. As reference example, in Fig. 1, Op4 occupies the third position of the production cycle.

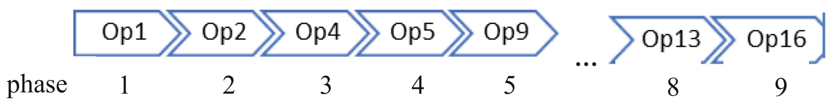



**Fig. 1.** Example of a part's production cycle

According to these assumptions, the PSI focuses on the operations needed to manufacture the different parts, independently from the specific position in the production cycle. Therefore, using the same set of operations for several parts increases the index value although they are arranged in different positions of the production cycle.

In the indicator formulation, the following notations are used.

| | |
|---|---|
| $j$ | operations, $j = 1, \ldots, J$ |
| $k, k_1, k_2$ | parts, $k, k_1, k_2 = 1, \ldots, K$ |
| $p$ | phase of production cycle, $p = 1, \ldots, P_k$ |

While the parameters are:

$$C_{kjp} = \begin{cases} 1 \text{ if operation j is performed in phase p to produce part k} \\ 0 \text{ otherwise} \end{cases} \quad \text{with} \quad \sum_{j=1}^{J} C_{kjp} = 1$$

$P_k$ total length of the production cycle of part k with $P_k \leq J$

The introduced parameters include information about the production cycles of the different parts. Hence, they are used to compute the average value of the production cycles length $\overline{V}$ through (1) and the total number of couples of different parts $D$ using (2).

$$\overline{V} = \frac{\sum_{k=1}^{K} P_k}{K} \tag{1}$$

$$D = \frac{K!}{2! \cdot (K-2)!} = \binom{K}{2} \tag{2}$$

As previously mentioned, the PSI evaluates the degree of common operations used during the production. It is defined according to (3) as the ratio between the average number of common operations $\overline{S}$ and the average length of the production cycles $\overline{V}$.

$$PSI = \frac{\overline{S}}{\overline{V}} \qquad PSI \in [0, 1] \tag{3}$$

The average number of shared operations $\overline{S}$ is get considering each couple of different parts $k_1$ and $k_2$. Fixed the pair, their production cycles are scanned looking for each operation $j$ in any phase $p$ performed for both the parts. The number of common operations for a given pair of parts $\sigma_{k_1 k_2}$ is obtained through the following Eq. (4).

$$\sigma_{k_1 k_2} = \sum_{j=1}^{J} \left[ \left( \sum_{p=1}^{P_{k_1}} C_{k_1 jp} \right) \cdot \left( \sum_{p=1}^{P_{k_2}} C_{k_2 jp} \right) \right] \tag{4}$$

The total sum of the common operations for each different pair is divided by the total number of pairs $D$.

$$\overline{S} = \frac{\sum_{k_1=1}^{K-1} \sum_{k_2=k_1+1}^{K} \sigma_{k_1 k_2}}{D} \tag{5}$$

Based on its structure, the value of the PSI lies in the range [0,1]. The value is close to 0 if the parts share few components compared to their average length whereas the more components they share, the higher the index value will be, enhancing the possibility to use product platforms and the DPD strategy.

Applying the DPD strategy is a subjective decision for a company: because it involves many context-specific drivers, the same PSI result may lead to different decision according to considerations made by each company. Starting from this observation, a threshold value of about 0.4 is suggested: a family of parts with a PSI equal or greater than this value represents a good candidate for the application of the DPD strategy and is admitted to further investigations. Otherwise, a PSI value lower than 0.4 is generally due to an excessive dissimilarity in the parts' production cycles, making the candidate family probably unsuitable for the implementation of DPD.

To exemplify the PSI calculation and use, let us assume a set of $K = 3$ parts produced through sequences of $J = 9$ different operations. Table 1 shows the production cycles for the considered set and their length, which is used in (1) to calculate the average length of the production cycle $\overline{V}$, equal to 4 in this reference case.

**Table 1.** Working cycles for the considered parts and respective length

| Parts | Work cycles | $V$ |
|---|---|---|
| K1 | Op1-Op2-Op3-Op4-Op5 | 5 |
| K2 | Op2-Op5-Op8-Op9 | 4 |
| K3 | Op7-Op9-Op6 | 3 |
| | | $\overline{V} = 4$ |

**Table 2.** Number of common operations

| $\sigma_{k_1 k_2}$ | K1 | K2 | K3 |
|---|---|---|---|
| K1 | – | 2 | 0 |
| K2 | | – | 1 |
| K3 | | | – |

Table 2 presents the number of common operations for every pair of parts $\sigma_{k_1 k_2}$: because of the structure of the example data set, made of 3 parts, the total number of couples involving different parts $D$ is equal to 3, with parts K1 and K2 sharing the maximum number of common operations (Op2 and Op5).

Starting from these values, the numerator of the PSI is calculated as:

$$\overline{S} = \frac{(2 + 0 + 1)}{3} = 1$$

and, following (3),

$$PSI = \frac{1}{4} = 0.25$$

The low result of the indicator reflects the significant difference in the part's production cycles, excluding the 3 examined parts from further investigation for the application of DPD.

An extensive application of the proposed index within an industrial company based in the Emilia-Romagna territory follows in the next section.

## 3 Case Study and Discussion

A real industrial case study is presented for illustration. The case company produces fixtures and windows frames through a set of assembly operations involving different components to obtain a wide product variety.

The considered fixtures family consists of $K = 16$ parts, each of which is manufactured through a different sequence of $J = 13$ possible operations. Table 3 shows the part production cycles.

**Table 3.** Part production cycles

| Parts | Production cycles |
|---|---|
| K1 | Op1-Op3-Op5-Op6-Op7-Op8-Op10-Op11-Op12-Op13 |
| K2 | Op1-Op3-Op4-Op6-Op7-Op8-Op10-Op11-Op12-Op13 |
| K3 | Op1-Op3-Op5-Op6-Op7-Op8-Op10-Op11-Op12 |
| K4 | Op1-Op3-Op4-Op7-Op8-OP10-Op11-Op12 |
| K5 | Op1-Op3-Op5-Op6 |
| K6 | Op1-Op3-Op4-Op6 |
| K7 | Op1-Op3-Op5-Op6-Op7-Op8 |
| K8 | Op1-Op3-Op4-Op6-Op7-Op8 |
| K9 | Op2-Op3-Op5-Op6-Op7-Op8-Op9-Op10-Op11-Op12 |
| K10 | Op2-Op3-Op4-Op6-Op7-Op8-Op9-Op10-Op11-Op12 |
| K11 | Op2-Op3-Op5-Op6-Op7-Op8-Op10-Op11-Op12 |
| K12 | Op2-Op3-Op4-Op6-Op7-Op8-Op10-Op11-Op12 |
| K13 | Op2-Op3-Op5-Op6 |
| K14 | Op2-Op3-Op4-Op6 |
| K15 | Op2-Op3-Op5-Op6-Op7-Op8 |
| K16 | Op2-Op3-Op4-Op6-Op7-Op8 |

Analysing the production cycles in Table 1, several operations are commonly used for more than one part. As reference example, the operation Op3 is included in the production cycle of every part contained in the analysed set. Because of this noticeable sharing of operations, a high value of the PSI is expected.

To determine this value, the average length of the production cycles $\overline{\mathrm{V}}$ and the total number of couples of different parts D are evaluated for the depicted scenario. The average production cycles length, i.e., $\overline{\mathrm{V}}$, is of about seven operations, while the combination of the total parts, i.e., D, produces 120 couples of different parts, as described below.

$$\overline{\mathrm{V}} = \frac{115}{16} \approx 7,19\,\text{operations}$$

$$\mathrm{D} = \frac{16!}{2! \cdot (16-2)!} = 120\,\text{different pairs of parts}$$

According to the formulation of the PSI (3), the number of common operations is evaluated for each pair of different parts and collected in the Table 4. For example, part K1 shares 9 operations with K2 whilst only two with K14.

**Table 4.** Number of common operations for each couple of parts

| $\sigma_{k_1k_2}$ | K1 | K2 | K3 | K4 | K5 | K6 | K7 | K8 | K9 | K10 | K11 | K12 | K13 | K14 | K15 | K16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K1 | – | 9 | 9 | 7 | 4 | 3 | 6 | 5 | 8 | 7 | 8 | 7 | 3 | 2 | 5 | 4 |
| K2 | | – | 8 | 8 | 3 | 4 | 5 | 6 | 7 | 8 | 7 | 8 | 2 | 3 | 4 | 5 |
| K3 | | | – | 7 | 4 | 3 | 6 | 5 | 8 | 7 | 8 | 7 | 3 | 2 | 5 | 4 |
| K4 | | | | – | 2 | 3 | 4 | 5 | 6 | 7 | 6 | 7 | 1 | 2 | 3 | 4 |
| K5 | | | | | – | 3 | 4 | 3 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 |
| K6 | | | | | | – | 3 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 |
| K7 | | | | | | | – | 5 | 5 | 4 | 5 | 4 | 3 | 2 | 5 | 4 |
| K8 | | | | | | | | – | 4 | 5 | 4 | 5 | 2 | 3 | 4 | 5 |
| K9 | | | | | | | | | – | 9 | 9 | 8 | 4 | 3 | 6 | 5 |
| K10 | | | | | | | | | | – | 8 | 9 | 3 | 4 | 5 | 6 |
| K11 | | | | | | | | | | | – | 8 | 4 | 3 | 6 | 5 |
| K12 | | | | | | | | | | | | – | 3 | 4 | 5 | 6 |
| K13 | | | | | | | | | | | | | – | 3 | 4 | 3 |
| K14 | | | | | | | | | | | | | | – | 3 | 4 |
| K15 | | | | | | | | | | | | | | | – | 5 |
| K16 | | | | | | | | | | | | | | | | – |

The sum of the elements in the matrix is divided by the number of different part pairs $D$ to obtain the average number of common operations for the considered variety $\overline{S}$. This value is used with the average length of the production cycle $\overline{V}$, calculated before, to evaluate the PSI, as in the following.

$$\overline{\mathrm{S}} = \frac{554}{120} \approx 4,62$$

$$\mathrm{PSI} = \frac{\overline{\mathrm{S}}}{\overline{\overline{\mathrm{V}}}} \approx 0,64 \rightarrow 64\%$$

As expected, the obtained medium-high value of the PSI confirms the significant sharing of operations within the part production cycles. The PSI value can be considered as a measure of the production mix aptitude to create platforms, i.e., the higher the index value, the higher the suitability of the application of product platform design methods. For the considered production mix, the PSI is about 64%, greater than the suggested threshold of 40%. Based on this result, the possibility of implementing a DPD strategy identifying common platforms from which deriving the different parts should be taken into consideration.

## 4 Conclusions and Future Research

Dynamic customer requirements and instable market demands are responsible of the proliferation of product variety. In this changeable context, the Delayed Product Differentiation (DPD) rose as an effective strategy implemented by several industrial companies to best cope with the product variety, by means of the so-called product platforms. Platforms are defined as a set of sub-systems and interfaces forming a common structure form which a stream of derivative variants can be efficiently produced and developed. Despite a set of models and methods for product platforms design is available in current literature, preliminary indicators assessing the feasibility and convenience of implementing the DPD strategy in industrial companies are missing. To fill this gap, this working paper proposes a preliminary indicator to assess the similarity among a set of parts, i.e., product variants, according to their production cycle, acting as a first criterion to assess the feasibility of implementing the DPD strategy. The application of the proposed indicator to an operative industrial instance showcases its effectiveness to suggesting to the company whether to implement the DPD or to using traditional production strategies. Future research deal with the extension of the indicator panel to include relevant issues not considered at this stage, e.g., production cycle precedence constraints, etc., as well as the development of models and tools for the effective product platforms design able to overcome the limitations of the models available in current literature.

## References

1. AlGeddawy, T., ElMaraghy, H.: Product variety management in design and manufacturing: challenges and strategies. In: Enabling manufacturing competitiveness and economic sustainability, pp. 518–523. Springer, Berlin, Heidelberg (2012) https://doi.org/10.1007/978-3-642-23860-4_85
2. ElMaraghy, H., et al.: Product variety management. CIRP Annals **62**(2), 629–652 (2013)
3. Hague, R., Dickens, P., Hopkinson, N.: Rapid Manufacturing: An Industrial Revolution for the Digital Age. John Wiley and Sons (2006)
4. Christophe, F., Bernard, A., Coatanea, E.: RFBS: a model for knowledge representation of conceptual design. CIRP Ann. **59**(1), 155–158 (2010)

5. Christophe, F., Sell, R., Bernard, A., Coatanea, E.: OPAS: ontology processing for assisted synthesis of conceptual design solutions. In: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, vol. 49026, pp. 249–260) (2009)
6. Qin, Y., Wei, G.: Product configuration flow from obtaining customer requirement to providing the final customized product. J. Softw. **7**(2), 308–315 (2012)
7. Rizzi, C., Regazzoni, D.: Systematic innovation in the management of product variants. In: Proceedings of 16th CIRP International Design Seminar, Design & Innovation for Sustainable Society, Kananaskis, Alberta, Canada (2006)
8. ElMaraghy, H., AlGeddawy, T.: New dependency model and biological analogy for integrating product design for variety with market requirements. J. Eng. Des. **23**(10–11), 722–745 (2012)
9. Bortolini, M., Calabrese, F., Galizia, F.G., Mora, C.: A three-objective optimization model for mid-term sustainable supply chain network design. Comput. Ind. Eng. **168**, 108131 (2022)
10. Mourtzis, D., Fotia, S., Boli, N., Pittaro, P.: Product-service system (PSS) complexity metrics within mass customization and Industry 4.0 environment. Int. J. Adv. Manuf. Technol. **97**(1–4), 91–103 (2018). https://doi.org/10.1007/s00170-018-1903-3
11. Gupta, D., Benjaafar, S.: Make-to-order, make-to-stock, or delay product differentiation? a common framework for modeling and analysis. IIE Trans. **36**(6), 529–546 (2004)
12. Galizia, F.G., ElMaraghy, H., Bortolini, M., Mora, C.: Product platforms design, selection and customization in high-variety manufacturing. Int. J. Prod. Res. **58**(3), 893–911 (2020)
13. Simpson, T.W., Siddique, Z., Jiao, R.J.: Product Platform and Product Family Design: Methods and Applications. Springer Science and Business Media, New York (2006)
14. Ben-Arieh, D., Easton, T., Choubey, A.M.: Solving the multiple platforms configuration problem. Int. J. Prod. Res. **47**(7), 1969–1988 (2009)
15. ElMaraghy, H., Abbas, M.: Products-manufacturing systems co-platforming. CIRP Ann. **64**(1), 407–410 (2015)
16. Zhang, Q., Peng, W., Lei, J., Dou, J., Hu, X., Jiang, R.: A method for product platform planning based on pruning analysis and attribute matching. J. Intell. Manuf. **30**(3), 1069–1083 (2017). https://doi.org/10.1007/s10845-017-1305-7

# Urban Food Production Digital Twin: Opportunities and Challenges

Peter Ball(✉) and Ehsan Badakhshan

School for Business and Society, York, UK
{peter.ball,ehsan.badakhshan}@york.ac.uk

**Abstract.** Populations are moving to urban locations and, with the rise in automation in both manufacturing systems and agricultural systems, are increasingly detached from where and how food is sourced and processed. The trend has been for larger and more intense production systems to move beyond the urban boundary that have both environmental as well as social consequences. Technological developments in hardware and software are enabling distributed, small scale, efficient, clean production which can be located within urban boundaries. This research has explored how food production in an urban center for local supply can be modeled using a digital twin. The focus is on a vertical, container farm and the supply to local customers using typical manufacturing and supply chain framing. In presenting the modeling capability and results, the paper brings out the challenges of modeling semi-automated production and opportunities for extending the design of the food system to impact on environmental performance. The paper concludes with consideration of wider application and the social and environmental impacts.

**Keywords:** Food system · Modeling · Digital twins · Urban production · Container farm

## 1 Introduction

The imperative of sustainability, especially environmental sustainability, has been steadily growing in prominence in practice and in academia evidenced by the public prominence, corporate sustainability strategy publications and academic paper publications. This has been reinforced and broadened by the agreement and widespread use of Sustainable Development Goals (SDGs) [1]. More recently the language of 'netzero' has grown within the UK as a result of government policy [2]. As a consequence of the causes of climate change and the imperative for fundamental changes to our approaches to production and consumption, existing norms of production, business models, etc. are being challenged [3].

One of the major consequences of globalization is the separation of production and consumption. Here production has been intensified and centralized for efficiency [4]. Consequently, the dispersed population is far from production in terms of both distance and understanding. The resultant consumption behaviors and generation of wastes are separated from production meaning closed-loop, circular economy principles


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 331–340, 2023.
https://doi.org/10.1007/978-981-19-9205-6_32

[5] are potentially limited due to the lack of motivation and opportunity to extract the highest value, energy consuming due to distances involved and sub-optimal due to lack opportunities to use locally. The environmental impacts of the lifecycle are at best hidden and at worst unknown.

Given such structural challenges for circularity to reduce impact and the willingness to challenge current methods, then localized production [6] and consumption could be a viable, less impactful alternative. Advances in hardware offer potential for small scale production [6] and advances in digital offer potential [7], particularly on visibility, brokerage and optimization.

This research considers how digital technology (specifically twins) can be used in urban production (specifically food) against local demand and how impacts can be captured. In more detail, the research considers how a vertical (container) farm as the production system using standard manufacturing and supply chain concepts can be modeled for operational improvement. The research seeks to address: How can urban food systems be modeled to consider production efficiency and environmental impact?

The paper is structured to use a literature review as foundation to confirm the research question and then justifies the methodology to apply the concept of a digital twin to optimize the production and supply. The discussion brings out the challenges and opportunities for urban production generically before conclusions identify opportunities for further research.

## 2 Exploring Small Scale, Local Production

This literature review considers research on three areas of production localization, production miniaturization and production digital twins before considering how the learning from each of these can be combined to explore a digital twin of small scale, local, urban production.

### 2.1 Production Localization

Against the backdrop of globalization and the Ford model of production that has driven intensified, global production [4], is growing work on localized [6] and distributed [7] manufacturing. Whilst large factories may be efficient, their regional and global siting of brings challenges for logistics and particularly environmental impacts [8].

The ability to produce locally has potential environmental benefits, not just in logistics but also in opportunities to use wastes locally through circular economy principles [9]. Locally can be interpreted in different ways from national to regional to specific communities. Potentially this could be in central urban areas or even within building complexes, such as hospitals [7], and provide opportunities for greater user engagement and personalization [7].

From a sustainability perspective, assuming localized production is economic, there are potential environmental and social benefits too. Environmental impacts can be felt through use of local materials, reduced logistics and potentially the exploitation of wastes such as heat. Social benefits can come from community engagement in production [10] and well as the use of local labor and quality of life [11].

### 2.2 Production Miniaturization

The consequence of production localization is the necessity to reduce the size of the production system to be able to efficiently produce to the lower production volumes. Technology developments enable small production systems to be operated efficiently. Additive manufacture is one such technology to enable small-scale production [6, 11] but this is not the only means.

There are examples of other forms of localized production, some of which are mobile. Truck-based is one such example for beer canning [12] as well as using shipping containers [13, 14] more generally. A mobile manufacturing system [15] may be designed to be frequently moved or constructed and moved once as in the case of vertical container farms [16]. In summary, there are examples of the principles, however, in practice implementations are far less numerous than the breadth and quantity of published papers.

### 2.3 Production Digital Twins

The advance of digital technologies has led to the conceptualization of a portfolio of complementary technologies collectively termed as Industry 4.0 [17] or simply digital. One of these technologies is the digital twin [18] that mirrors the real system with a simulation model of that system.

There are different types of digital twin used in practice and academia ranging from a digital model that is an unconnected copy of the real system, to a digital shadow that draws live data from the real system, to a digital twin that draws live data and autonomously issues decisions back to the real system [19]. For a digital twin that is anything other than a model, other digital technologies including sensors, communications and machine learning [20] are needed in support.

Digital twins have been applied in numerous ways including warehouse management [21], food supply chains [22], automotive [23], automated flow shops [24] and robotic cells [25]. These examples seek to improve the operational efficiency, increase resilience, decrease cost or, in a few cases, reduce environmental impact through energy reduction. In summary, these examples demonstrate that digital twin technology has the potential to model a wide variety of applications and scales as well as assess economic and environmental impact.

### 2.4 Opportunity for Digital Twins of Small Scale, Local, Urban Production

The above literature review has brought out the changes in production configuration in the areas of localization and miniaturization as well as the role of digital twins. Localization brings out the need for digital or Industry 4.0 technologies, of which digital twins is just one. Whilst enabler of additive manufacturing is frequently cited in the literature, the examples above show that the principles are applicable to small scale production from production cells to food production.

There are gaps in the knowledge in local, small-scale production. Aside for the lack of examples generally, there is an absence of small-scale food production in the context of local supply modeled using digital twins. Additionally, there is a lack of insight into the modeling of the environmental impacts using digital twins here. This therefore led to the research question of: How can urban food systems be modeled to consider production efficiency and environmental impact?

## 3 Methodology

This research sought to understand how small-scale, local, urban production and supply could be modeled. Given the lack of available literature in the area, the research was necessarily exploratory to address the 'how' question above.

A single case of a vertical (specifically container) farm was selected out of convenience as it was located within the York city center at Spark:York and operated by the University of York. The farm is operated semi-automatically with manual germination, sowing, harvesting and packing operations and autonomous growing system controlled through lighting, water supply and temperature. Access to the farm's Ostara [26] operating system meant the production schedule and farm conditions could be accessed remotely and therefore connected to a digital model. Lanner Group Ltd's Witness simulation product [27] was selected as the system to pursue the creation of a digital twin given its ability to model production and supply systems and the connectivity to external data sources.

## 4 Modeling Local Production

Spark:York is an entertainment and enterprise complex formed of shipping containers in York city center in the UK. The hydroponic farm was located on the first floor on the complex in a container pre-fitted by LettUs Grow Ltd. The leafy green products were germinated from seed, grown in the growing beds (under LED lighting, nutrient, water and temperature control), harvested and packed within the container. The products from the farm were supplied to the local catering outlets within Spark and beyond. Demand was gathered from the catering outlets and complemented with predictions of wider demand. The consolidated demand was the key input to the optimization and simulation model that would provide farm input data and model the process.

The digital twin system was constructed using the Witness software and supporting optimization software. The optimization was configured to create a production schedule which minimizes the total tardiness which is determined by calculating the difference between a crop order due date ($DD_c$) and its harvest time ($HD_c$) known as tardiness and aggregating the results (Formulated in Eq. (1)). Equation (2) calculates the harvest time ($HD_c$) of a crop order using its sowing date ($SD_c$), germination time ($GerT_c$) and growing time ($GrwT_c$). Equation (3) ensures that the sowing date of a crop order is between the schedule start time ($SST$) and the schedule finish time ($SFT$). To prevent waste, Eq. (4) ensures that the difference between a crop order due date and its harvest date is less than perishability period for the crop ($PP_c$).

$$Min\,Total\ tardiness = \sum_{c=1}^{n} DD_c - HD_c \tag{1}$$

$$HD_c = SD_c + GerT_c + GrwT_c \quad \forall c \tag{2}$$

$$SST \leq SD_c \leq SFT \qquad \forall c \tag{3}$$

$$0 \leq DD_c - HD_c \leq PP_c \qquad \forall c \tag{4}$$

The generated production schedule was then input in Witness simulation model to test the production (or logistics) and make recommendations to the farm operator. The model takes in live updates from the farm as the production schedule was implemented. To minimize the risk in this research, the production schedule was implemented manually rather than autonomously into the farm's operating system. This food production system of inputs, transformation, outputs and supply shares the characteristics typical of any production system. Perhaps unusually for production systems, the germination and growing process are highly predictable and subject to very low process time variation. The digital twin model is shown in Fig. 1.

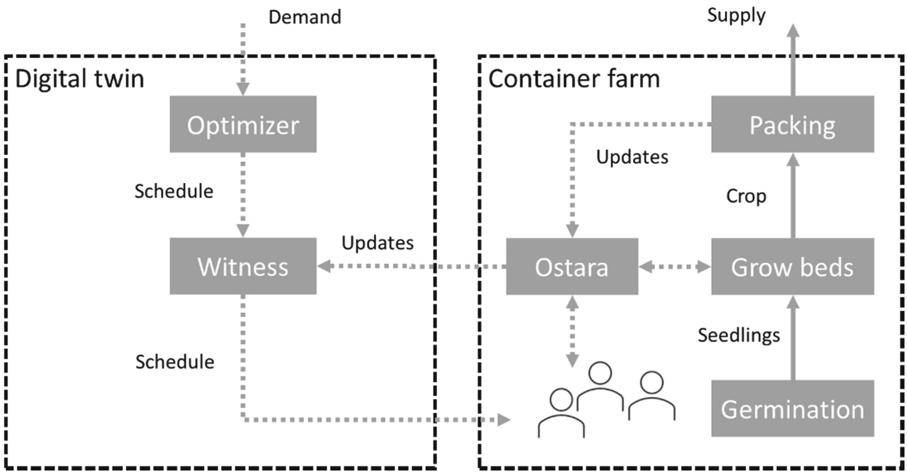



**Fig. 1.** Schematic of the data flows between the digital twin of the container farm

The model was run over many weeks to model the scope of germination, growing, harvesting and supply to the local businesses. Results that are typical of the digital twin are shown in Fig. 2. The results show the typical production systems metrics as well as the facility metrics of energy and water that can be used for both economic and environmental assessment. No social sustainability modeling was undertaken for this work, however, the location and resulting visibility of the operation of the farm gives potential for a broad social sustainability assessment.

The results are typical of any production system operation and modeling with the ability of the model to capture the utilization of the facility as well as the flow of product through it. It also addresses the environmental metrics that are starting to appear in production systems visual management performance boards. The ability to incorporate this range of metrics gives the potential for multi-criteria optimization not just of utilization and flow but also the environmental impact.

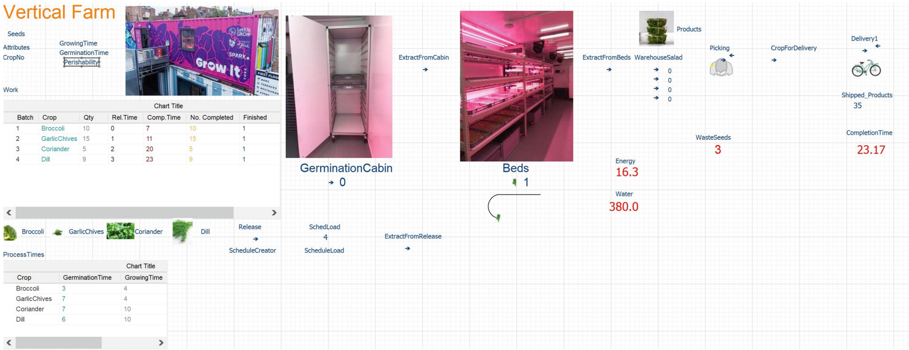



**Fig. 2.** Example of the onscreen results output from the digital twin of the container farm

## 5 Discussion

This research on modeling an urban production system is part of a wider program of research advancing how digital twins can be used for production and supply chain systems considering the environmental impacts. Importantly this program of work contributes to environmental assessment, circularity and urban/local aspects together. Implicitly this is challenging whether production scale and location must be large and centralized to be efficient and low impact. Specifically, here the focus was on how can urban food systems be modeled to consider production efficiency and environmental impact.

### 5.1 Urban Supply Chain Conceptualization

Food production (i.e. the growing and harvesting stages) and food processing (i.e. typical manufacturing systems operations) are typically considered as two separate systems and "farm-to-fork" is typically too complex to be considered together. Factors including scale, lead-time, complexity, discipline and control result in systems improvement being compartmentalized, improved and optimized separately. The above factors are less significant in this work hence give potential for wide scope of analysis. Although the processing and consumer activities are not modeled here, conceptually and practically they have potential for immediate inclusion.

The language of production systems and supply chain is used in this paper to draw on technical manufacturing language to guide the conceptual modeling, implementation techniques and metrics. This is not the typical language considered for this type of operation. This application of engineering thinking to an agricultural system offers an opportunity to apply concepts to small scale, urban production and supply generally. This can be both from the sizing of the production to efficiently meet local demand as well as the conceptualization and the influence on scope 3 emissions which can be diffuse, hard to establish and hard to influence.

The circular economy concept promotes the retention of wastes for further use. The shorter the loops conceptually the greater the potential value retention. With a small urban scenario the waste volumes are low but so too can be the cost of transportation. The close proximity of waste sources and sinks offers an opportunity to think differently on how energy wastes (e.g. heat) and material wastes (e.g. agri-food nutrients) are captured and traded at a local level.

### 5.2 System Behavior Challenges

Whilst not shown in the results in this paper, the production flow is highly predictable given that the farm management system is able to tightly control temperature and light levels. This stability results in highly predictable lead-times, rapid transfer to customers and therefore the food consumers. This early predictability of the farm-to-fork flow contrasts with the later external variability of consumers eating the produce (in the food operating businesses, FOBs, within Spark and beyond). The close coupling of growing stages with the processing stage (e.g. by an FOB) and the consumption stage of perishable food products leaves little room for buffering between stages.

There are opportunities here for nutrition optimization through balancing the mix of crop type grown with the time after harvesting that consumers consume the available stock. Overall, this contrasts with typical technical production systems for non-perishable products which are more complex, have internal variability with longer, less coupled supply chains allow greater buffering of the external variability.

### 5.3 Digital Twin Advance

One of the modeling challenges that also features in engineering production systems is the semi-automated nature of production. Some parts of the farm modeling could be implemented as a full digital twin with automated data transfer from physical twin to digital twin, autonomous decision making and actioning the decision in the physical twin. For example, the collection of production status, demand and return of an optimized schedule. However, the manual tasks of seed germination, planting, harvesting and packaging mean that some parts of the farm modeling can only be implemented as a digital shadow. For example, manual data entry on the germination, sowing and harvesting and manual actioning of model recommendations. The combination of manual, automated and autonomous digital twins is an under-researched area.

There is potential to develop the twin for functionality beyond immediate operational area. Technically, there is potential for multi-scale, hierarchical modeling in the digital twin as here the modeling is at a production logistics level whilst other forms of modeling are at the ‘machine’ or crop growing level. Socially, as the graphical features of the digital twin are improved there is potential for videos or live feeds of the operation for online access to complement the physical visual access within Spark. Currently the twin cannot deliver a live web display for virtual access.

## 6 Conclusions

This paper has presented the results from digital simulation modeling of an urban food production system and local supply. The work has documented the ambition to create a digital twin and show how production and supply can be modeled and use live production data feeds to update the model.

The research has shown how local, small-scale production and supply can be modeled and the output and environmental impact through energy and water consumption uncovered. Whilst the focus of the production unit was for a farm growing leafy greens, conceptually the production was the same as a technical production system converting raw material inputs to valuable outputs. Further, the modeling has examined the variability which at production system level is very low compared to wider production types yet potentially high variability at supply chain level given the short chain to consumer purchasing. The research has shown the potential for modeling urban, small-scale production and local supply chains. Issues arising in the modeling included how to get access to a combination of digital automated data as well as manual activities and how to use a digital twin in a way that autonomous decision making can only apply to part of the production and supply operation.

The work has uncovered potential avenues for new research. The first is to apply the learning here to other urban product production and supply chain scenarios. Given the potential for small scale, distributed manufacturing then better understanding of local product and wastes flows would be of value. Following on from this, with higher number of production locations in a locality and associated movements of resources brings potential for consideration of circularity and resulting changes in environmental impact. Modeling with digital twins gives the potential to understand the efficiency and environmental performance locally compared to regionally or globally. Finally, the presence of production in localities opens up the potential for engaging the general public and consideration of the social impacts arising from awareness of the provenance and environmental impact of the products they use or consume. Whilst modeling is not easily suited for social impact, it has inherent potential for communication of the provenance and environment performance.

**Acknowledgements.** This work has been funded by the UK Research and Innovation (UKRI) research body, EPSRC through grant EP/T024844/1 "A Multiscale Digital Twin-Driven Smart Manufacturing System for High Value-Added Products". We would like to thank the Prof Katherine Denby and Dr Alana Kluczkovski from University of York and the FixOurFood, Transformations to Regenerative Food Systems UKRI BBSRC grant BB/V004581/1 funded project for their contributions to the research and access to the vertical container farm and data. We would like to thank the staff at LettUs Grow Ltd for their technical advice and API access to the farm's control system to enable live data transfer to the digital model.

## References

1. UN: Transforming our world: the 2030 agenda for sustainable development. A/RES/70/1, United Nations (2015)
2. UK Net Zero: https://www.gov.uk/government/publications/net-zero-strategy. Accessed 27 May 22
3. Stubbs, W., Cocklin, C.: Conceptualizing a sustainability business model. Organ. Environ. **21**(2), 103–127 (2008)

4. Shi, Y., Gregory, M.: International manufacturing networks - to develop global competitive capabilities. J. Oper. Manag. **16**(2–3), 195–214 (1998)
5. Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J.: The circular economy - A new sustainability paradigm? J. Clean. Prod. **143**(1), 757–768 (2017)
6. Kleer, R., Piller, F.T.: Local manufacturing and structural shifts in competition: market dynamics of additive manufacturing. Int. J. Prod. Econ. **216**(10), 23–34 (2019)
7. Srai, J.S., et al.: Distributed manufacturing: scope, challenges and opportunities. Int. J. Prod. Res. **54**(23), 6917–6935 (2016)
8. Köhler, J.: Globalization and sustainable development: case study on international transport and sustainable development. J. Environ. Dev. **23**(1), 66–100 (2013)
9. Moreno, M., Charnley, F.: Can re-distributed manufacturing and digital intelligence enable a regenerative economy? an integrative literature review. In: Setchi, R., Howlett, R.J., Liu, Y., Theobald, P. (eds.) Sustainable Design and Manufacturing 2016. SIST, vol. 52, pp. 563–575. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-32098-4_48
10. 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.) Sustainable Design and Manufacturing 2016. SIST, vol. 52, pp. 577–588. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-32098-4_49
11. Ford, S., Despeisse, M.: Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. J. Clean. Prod. **137**, 1573–1587 (2016)
12. Pitts, E.R., Witrick, K.: Brewery packaging in a post-COVID economy within the United States. Beverages **7**(1), 14 (2021)
13. Zadra, R.: Modular Microfactories. World Manufacturing Foundation (2021)
14. MTC: What is factory in a box? https://smartmanufacturingaccelerator.co.uk/what-is-factory-in-a-box/ Accessed 27 May 22
15. Alix, T., Benama, Y., Perry, N.: Reconfigurable manufacturing system design. In: Grabot, B., Vallespir, B., Gomes, S., Bouras, A., Kiritsis, D. (eds.) APMS 2014. IAICT, vol. 440, pp. 352–359. Springer, Heidelberg (2014). https://doi.org/10.1007/978-3-662-44733-8_44
16. LettUsGrow: Indoor farming for a better future. https://www.lettusgrow.com/ Accessed 27 May 22
17. Schuh, G., Rudolf, S., Riesener, M.: Design for industrie 4.0. In: Proceedings of the 14th International Design Conference (DESIGN), pp. 1387–1396, Dubrovnik, Croatia (2016)
18. Ivanov, D., Dolgui, A.: A digital supply chain twin for managing the disruptions risks and resilience in the era of Industry 4.0. Prod. Plan. Control **32**(9), 775–788 (2021)
19. Grieves, M.: Digital twin: manufacturing excellence through virtual factory replication. White Paper **1**, 1–7 (2014)
20. 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)
21. Baruffaldi, G., Accorsi, R., Manzini, R.: Warehouse management system customization and information availability in 3pl companies: a decision-support tool. Ind. Manag. Data Syst. **119**(2), 251–273 (2019)
22. Burgos, D., Ivanov, D.: Food retail supply chain resilience and the COVID-19 pandemic: a digital twin-based impact analysis and improvement directions. Transp. Res. E: Logist. Transp. Rev. **152**, 102412 (2021)
23. Park, K.T., Son, Y.H., Noh, S.D.: The architectural framework of a cyber physical logistics system for digital-twin-based supply chain control. Int. J. Prod. Res. **59**(19), 5721–5742 (2020)
24. 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)

25. Ng, A.H.C., Bandaru, S.: Virtual factories with knowledge-driven optimization as a new research profile. In: Säfsten, K., Elgh, F. (eds.) SPS2020: Proceedings of the Swedish Production Symposium, October 7–8, 2020. IOS Press (2020). https://doi.org/10.3233/ATDE200155
26. Ostara: Ostara farm management and control software for indoor farms. https://www.lettusgrow.com/ostara-farm-management Accessed 24 Jun 22
27. Witness: Witness simulation software. https://www.lanner.com/en-gb/ Accessed 24 Jun 22

# Application of Education for Sustainable Development (ESD) as a Route to Overcoming Barriers in Designing Circular Economy (CE) Educational Material

Alex Mifsud(✉), Antonio Sanchez-Vazquez, and Chris Callaghan

Anglia Ruskin University, East Road, Cambridge CB1 1PT, UK
{alex.mifsud,antonio-sanchez-vazquez,chris.callaghan}@aru.ac.uk

**Abstract.** Designing Circular Economy (CE) educational programmes to a diverse group of learners presents challenges and opportunities. This paper shares insights from the development of a CE educational programme for disadvantaged learners through the BLUEPRINT project. It explores the pivotal role Business Schools in Higher Education Institutions (HEI) play by serving as a bridge between business and society in the transition to a CE. Through the lens of pedagogical approaches from education for sustainable development (ESD) theories, the paper discusses CE educational programmes and explores the barriers at a learner, academic institution, and stakeholders level. It presents the benefits of co-creation for the design of CE educational material to equip learners with the skills required to deal with the ever-changing landscape in our society, environment, and economy. The paper makes recommendations on the application of ESD to turn challenges into opportunities for HEI when developing CE educational materials for the community which require a different approach to those for the HEI curriculum.

**Keywords:** Circular economy · Education for sustainable development · Higher education

## 1 Contextual Background

### 1.1 BLUEPRINT Project

With the many definitions given to the Circular Economy (CE), 115 according to Kirchherr and Van Santen (2019), in this work we will not introduce another and refer the reader to the EU's and OECD's published definition (2022). We will however consider it from a functional perspective as a vehicle that can guide production and consumption in modern global society towards systems that are more sustainable than current linear models. Given its cross-disciplinary origins, we will take Boulding's seminal 1966 paper 'Economics of the Coming Spaceship Earth' as the first to introduce the concept. The basis for any economy, linear or circular, is production and consumption of products. Consumers and producers can adopt sustainable ways through developing the right skills


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 341–350, 2023.
https://doi.org/10.1007/978-981-19-9205-6_33

to both empower consumers to make sustainable choices, and to provide the workforce with training needed to work in a CE.

The BLUEPRINT to the Circular Economy project is a cross-border programme, funded by Interreg France Channel England to develop, promote, and implement strategies promoting CE among key stakeholders. It brings together Universities, local authorities, social enterprises, industry, and community-based charities, to deliver the programme over 3 years (2020–2023) to create new training opportunities for individuals at risk of economic exclusion by developing bespoke training that can be delivered to them to increase their employment opportunities.

### 1.2 The Role of Business Schools in Lifelong Learning

The BLUEPRINT project partner entrusted with leading the design and development of a CE educational programme is the Faculty of Business and Law at a British higher education institution (HEI). Business Schools contribute to society in different ways, such as by enabling entrepreneurship (Eesley and Lee, 2021), regional economic growth (Kochetkov et al., 2017), environmental citizenship (Lillah and Viviers, 2014), and business ethics (Sims, 2004), to name a few. Business education can also shape moral philosophies of students that guide their future behaviours in business (Neubaum et al., 2009), and in that its students span career stages, is a primary source of lifelong learning. Through community outreach, Business Schools can also facilitate linkages between academia itself and its industry and government partners in economic and social development (Ye et al., 2013). Economic growth and human development derives primarily from what Business Schools teach - the ability to combine resources - to manage. Given that climate change and environmental degradation may pose an existential threat (Haney, 2017; Mitchell and Callaghan, 2019; Mitchell et al., 2020), Business Schools may be in a unique position to drive the sustainability agenda, their students being part of the global cohorts of managers of businesses contributing to the crisis.

The CarringtonCrisp Report (2021) advocates that "employers would like a closer relationship with business schools to develop programmes relevant to the future of work. 79% are interested in co-creation of content whilst 77% would like short, inexpensive programmes that deliver relevant skills for employees." Organisations surveyed report change management; resilience/mindfulness; global mindset; ethics and ethical behaviour; and managing across cultures as five key skills needed for staff. On the other hand, a quarter of employees surveyed want learning providers to be known for challenging world views by combining innovative and critical thinking; seeking a culture of enterprise; engaging with start-ups and social entrepreneurs; and focusing on social responsibility. The CarringtonCrisp Report (2021) concurs with Tilbury et al. (2005) who argued for Business Schools to rise to the challenge of leading change through their academic research and practice by serving as "a critical link between the sustainability needs of businesses and curriculum offerings."

### 1.3 Circular Economy Education in Higher Education and Business Schools

HEI stakeholders are key to driving systematic changes toward CE as they provide guidance to other stakeholders and can inculcate a vision of CE-oriented eco-responsible citizenship (Serrano-Bedia and Perez-Perez, 2022). Introductory educational programmes are helpful in that they can foster debates (Kirchherr and Piscicelli, 2019). CE education best pedagogical practices such as interactivity, non-dogmatism, and reciprocity together with application of constructive alignment and problem-based learning can be particularly useful (Kirchherr and Piscicelli, 2019). Interactivity improves engagement and can make learning more enjoyable. A non-dogmatic approach can develop critical thinking skills, and reciprocity created by incorporating student feedback into courses can improve engagement.

### 1.4 Positioning Circular Economy Within the Pillars of Sustainability and the UN SDGs

Sustainability is widely known to comprise of three pillars: Society; Environment; and Economy. A transition towards a CE supports the pillars of sustainability and the UN Sustainable Development Goals. It offers solutions by placing society and economy in the context of sustainable limits and planetary boundaries. One of the most pressing and central questions of sustainability has been formulated as being that of 'intergenerational equity' (WCED, 1987). CE educational programmes can build skills and behavioural changes that address the consumption patterns of current generations to address the intergenerational equity debate.

## 2 Conceptual Background

### 2.1 Education for Sustainable Development (ESD)

Education is widely recognised as a pivotal lever in preparing for an uncertain and challenging future, as we settle deeper into the Anthropocene (UNESCO, 2014, UN SDG's, 2015). Never has there been more purpose and urgency to the sustainability challenge as planetary boundaries continue to be passed with severe and devastating effects (Rockström et al., 2009) that impact hardest on those most vulnerable. Global responses to these issues reflect an increasing awareness of the urgency of action required (IPCC, 2022) and there is growing recognition of the contribution Higher Education (HE) can make towards a better future (Blake et al., 2013; Ryan and Tilbury, 2013; Sterling, 2014). This momentum is supported by international frameworks, such as the United Nations Decade of Education for Sustainable Development (UNDESD) 2005–2014, and the Global Action Programme (GAP) on Education for Sustainable Development (ESD) (UNESCO, 2014; Buckler and Creech, 2014). However, with the global pandemic, energy and food security crises, and war in Ukraine, the pace of change is slow, reactionary and quite often sporadic.

Indeed, there is increasing evidence (McKeown & Hopkins, Cloud, Bourn, in Chalkley et al., 2009) and (UNESCO, 2014) of the need for more work to assist individuals in making changes in their decisions and actions for the benefit of the future of our planet and future generations around the world. Individuals need to be equipped with cognitive, practical, thinking, decision-making and problem-solving skills to feel adequately confident and sufficiently motivated to engage in a more sustainable lifestyle. The UNDESD signalled a recognition that education is a powerful tool to drive the changes in social attitudes required to protect future generations. Fien (2006) argues that "education for sustainable development is not a global imposition on countries and education systems but an invitation for them to explore the themes and issues, the objectives and the pedagogies that can make education locally relevant and culturally appropriate in the search for a better world for all."

ESD is a process whereby through teamwork, stakeholder engagement and decision making, teams across disciplines and social groups learn from each other as they explore options, identify solutions, and consider the consequences to the future for each. It not only provides learners with the knowledge and understanding to engage with sustainability themes, but also the skills and competencies to plan, motivate, and manage change towards a sustainable and resilient future. This pedagogical approach brings about ancillary benefits to learners. When learners are given the opportunity to observe their cognitive and emotional patterns on sustainability issues, it enhances their ability to manage the automatic flow of thoughts and establish more successful ways of seeing and responding to the world (Brown and Ryan, 2003).

### 2.2 Learner Engagement

Against a backdrop of seismic global events leaving communities, through no fault of their own without a job and a good quality of life, it is difficult to visualize a sustainable and resilient future. Citizen discontent gives rise to disconnect and loss of trust in those that hold the economic and political powers. A number of these would be classified as disadvantaged learners. Motivating these members of society into making a commitment towards reducing their impact on the environment poses serious difficulties. Fagan, in Stibbe (2009:200) proposed the creation of "a shared common space in education between people and professionals, and between traditional and non-traditional learners." The concept of shared common space builds on the richness of knowledge and skills within communities whilst drawing upon the pedagogical competencies typically found in academic institutions. This participatory pedagogical approach in the design of education material would represent the views and reflects the needs of a range of learners with diverse social and economic circumstance thus making it more likely to be accepted by the learners.

### 2.3 BLUEPRINT Disadvantaged Learners

CE educational programmes for disadvantaged learners can be developed through the concept of a shared common space for education. Skills for whole systems approaches, critical thinking and collaborative problem-solving will also be needed for private sector transformation (UNESCO, 2014). The CE educational programme for the BLUEPRINT project has potential to equip disadvantaged learners with the skills needed by working in collaboration with the social enterprise and local authority project partners.

## 2.4 Learner Competencies

Stemming from the ESD pedagogical approaches, learner competencies in Table 1 below are considered applicable when designing CE educational programmes:

**Table 1.** Learner competencies

| Future-orientated learning | Critical thinking and creativity | Interpersonal skills |
|---|---|---|
| Collaborative skills | Ability to demonstrate agency | Ability to manage change and uncertainty |

(UNECE Expert group, 2013, Wiek et al., 2011, Sterling, 2014).

It is useful to explore behavioural and educational psychology that can shed light on how to embed learner competencies and how these can be effectively embedded in educational programmes. de Bono (1991:18) argues that "in a complex society political decisions and pressures depend very much on individual thinking. If that thinking can see only narrow self-interest, or only an immediate future, then society becomes a power struggle for self-interest." When such statements are applied to the pressing issues of ecological destruction and climate change, it immediately becomes clear that thinking skills, systems thinking, experiential learning and problem-based learning need to be infused in CE educational materials. In so doing, individuals are not only equipped with the skills to lead a sustainable lifestyle but also with ones that provide them with the self-confidence needed to question the status quo, to become actively engaged in decisions, actions, and initiatives for a sustainable and resilient society.

Psychologists and behavioural scientists have long debated the roots and importance of human emotions (Arnold, 1960; Smith, 1991; Goleman, 1995, in Doppelt, 2008). Adult humans have the cognitive ability to create a distinction between emotions and action by controlling how they view and therefore think through situations. It follows that humans have the potential and ability to act purposely to adopt new ways of thinking and behaving that protect social and planetary well-being. CE educational programmes are intended to bring about these changes in the learners. Subsequently, it is important to consider the barriers that impede learners from change, and drivers that lead them to change their view of the world and by default their behaviour. As Doppelt (2008:69) rightfully argues "by understanding this intrinsic human ability to change, you can avoid actions that may impede the process…you can help facilitate and speed the change process." The trans-theoretical model of change (TTM) (Prochaska et al., 1994) can serve as a good tool when designing CE educational programmes. Doppelt (2008) has adapted it to better meet the requirements of sustainability related themes. Table 2 below, adapted for this paper, provides an overview of Prochaska's steps, with Doppelt's 5-D stages (in brackets) and how it can be used to provide support to disadvantaged learners in the BLUEPRINT project.

Through the identification of learner competencies and applying thinking and behavioural change techniques, learners stand a better chance of becoming effective actors for change in their respective communities.

**Table 2.** Change process and learner support (adapted from Prochaska, 1994, and Doppelt, 2008)

| Stages | Process of change | Learner support |
|---|---|---|
| Stage 1<br>Pre-contemplation<br>(Disinterest) | We have not started to think about changing (through lack of awareness or denial)<br>Something needs to capture our interest and cause us to see a need for change | Information alone will not necessarily create such an awareness |
| Stage 2<br>Contemplation<br>(Deliberation) | We begin to think about changing<br>We weigh up benefits vs costs of change; assess whether we have the capability of changing | Reinforcement of their ability, plus information which highlights the benefits of change |
| Stage 3<br>Preparation<br>(Design) | We plan for the change we are about to make<br>We work out the best way to change, gathering the tools and skills we need, and ensuring that our change will be successful | Provision of assistance and resources they need; encouraging them to maintain motivation and keep moving |
| Stage 4<br>Action<br>(Doing) | We begin the act of changing<br>We are susceptible to relapse in this stage as habits are yet to be formed | Continued reinforcement, and, where possible, measures to ensure that their change experience is positive |
| Stage 5<br>Maintenance<br>(Defence) | We are engaged in the new behaviour regularly and it becomes a habit<br>Chances of relapse are lower, although the change should not be taken for granted | Continued efforts to improve the reliability and stability of the environmental conditions in which the behaviour is being performed |

# 3 Discussion

## 3.1 Identification of Key Barriers in Circular Economy Education – the BLUEPRINT Project

A significant part of the BLUEPRINT project is the design and delivery of educational materials developed in consultation with project partners and stakeholders. The main target group of eligible learners are those classed as disadvantaged defined by Article 2.18 of the Regulation (EC) 800/2008. It is a far-reaching and wide-ranging definition and as Redmond and Walker (2009:126) point out, "serious issues are raised for educators seeking to design and deliver environmental education for small businesses who are a disparate group in need of individualized and specific programs.". Furthermore, of significance to the experiences gained from the BLUEPRINT project is the point made by Noe (2013) that any effective training involves the use of a training design process which starts with a needs assessment. Key barriers we identified during the BLUEPRINT Circular Economy educational programme design are:

- Perceived and in some instances real gaps between the learners and HEI.
- Complex and intricate project partners that each have varying realities in the community they serve.
- Wide definition for disadvantaged learner.
- Challenges in identification of learner needs.
- Establishing common ground across partners to build a contextually relevant educational programme.
- Competing educational needs from partners and learners that may be viewed as taking priority over skills for the CE.

### 3.2 Application of ESD to Overcome Key Barriers

There is no ‘one size fits all’ model for organisations, hence the logical approach for CE education programmes is to reflect this diverse reality by modelling elements into the programme that are truly needs-based and relevant to the context within which they are being implemented. If CE education for disadvantaged learners for social enterprise and local authorities is not introduced effectively and appropriately, there is the risk for it to lose support. The organisations involved in the BLUEPRINT project need some reassurance that any initiatives for their learners will meet their expectations as a route to creating the behavioural and societal transformation needed to transition to a more sustainable and resilient future. Hence this paper supports Lenglet (2014:124) when he states that “more and sounder research is needed on how ESD-inspired content and learning methods can make a real difference in getting people to move onto paths of sustainability.” Findings from UNESCO’s report, (2014:151) suggest that “short experiential training events, which focus on systems thinking and practical decision-making, and which challenge participants from different sectors to co-create solutions to real problems, are most effective.” CE educational programmes are ideal candidates for assisting the BLUEPRINT project disadvantaged learners to co-create solutions to challenges they and their communities are facing whilst also becoming part of the global transition to a more sustainable, equitable and resilient world.

## 4 Conclusion and Recommendations

Our recommendations reflect real world experiences from the BLUEPRINT project. We hope the recommendations offer guidance to academics creating educational content for learners in the community in collaboration with their external stakeholders. These are:

- HEI need to engage with the selected communities from the outset of the project to create an environment of shared learning space.
- Identify community groups with representation of disadvantaged learners to provide a platform where academics and learners conduct a needs assessment.
- Build a community of disadvantaged learners from a wide range of sectors and circumstances to provide depth and breadth that guides the co-creation of CE educational programme relevant to the learners.
- HEI enable learners to direct the design of the CE education programme.

- Establish strong links with social enterprises and stakeholders from the community to offer them the pedagogical expertise during the design of CE educational material for their learners.

We have discussed the role Business Schools and HEI play in the development of skills for business and community resilience for a greener future for all. The paper presented ways on overcoming barriers at the design stage through the application of participatory approaches and by borrowing insights from behavioural change and ESD pedagogical theories that can guide academics on developing a common learning space between themselves and the learners in the community.

**Acknowledgement.** The authors wish to acknowledge the BLUEPRINT to a Circular Economy - a project funded by the Interreg France (Channel) England Programme: Project No 206.

## References

Blake, J., Sterling, S., Goodson, I.: Transformative learning for a sustainable future: an exploration of pedagogies for change at an alternative college. Sustainability **5**(12), 5347–5372 (2013). https://doi.org/10.3390/su5125347

Boulding, K.E.: The Economics of the Coming Spaceship Earth. In: H. Jarrett (ed.) Environmental Quality in a Growing Economy, pp. 3–14. Baltimore, MD, Resources for the Future/Johns Hopkins University Press (1966)

Brown, K.W., Ryan, R.M.: The benefits of being present: mindfulness and its role in psychological well-being. J. Pers. Soc. Psychol. **84**, 822–848 (2003). https://doi.org/10.1037/0022-3514.84.4.822

Buckler, C., Creech, H.: Shaping the future we want: UN Decade of Education for Sustainable Development, final report. DESD monitoring and evaluation. UNESCO (2014)

CarringtonCrisp: The Future of Lifelong and Executive Education Report. CarringtonCrisp.com (2021)

Chalkley, B., Haigh, M., Higgit, D. (eds.): Education for sustainable development, papers in honour of the United Nations Decade of Education for Sustainable Development (2005–2014). Routledge, Oxon, UK (2009)

Commission Regulation (EC) No 800/2008. Declaring certain categories of aid compatible with the common market in application of Articles 87 and 88 of the Treaty. Official Journal of the European Union (2008)

De Bono, E.: Teaching thinking. Penguin Books, London (1991)

Doppelt, B.: The Power of Sustainable Thinking. Earthscan Ltd, London (2008)

Eesley, C.E., Lee, Y.S.: Do university entrepreneurship programs promote entrepreneurship? Strategic Management Journal (John Wiley & Sons, Inc.) **42**(4), 833–861 (2021). https://doi.org/10.1002/smj.3246

Fien, J.: A letter from the future: UNESCO and the Decade of Education for Sustainable Development. Aust. J. Environ. Educ. **22**(1), 63–70 (2006)

Fagan, G.: Citizen Engagement. In: Stibbe, A. (ed.) The Handbook of Sustainable Literacy: Skills for a changing world. Devon, Green Books Ltd. (2009)

Haney, A.B.: Threat interpretation and innovation in the context of climate change: an ethical perspective. J. Bus. Ethics **143**(2), 261–276 (2017). https://doi.org/10.1007/s10551-015-2591-7

IPCC: Summary for Policymakers, In: Pörtner, H.-O., Roberts, D.C., Poloczanska, E.S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A. (eds.) In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. In Press (2022)

Kirchherr, J., Piscicelli, L.: Towards an education for the circular economy (ECE): Five teaching principles and a case study. Resour. Conserv. Recycl. **150**, 104406 (2019). https://doi.org/10.1016/j.resconrec.2019.104406

Kirchherr, J., van Santen, R.: Research on the circular economy: A critique of the field. Resour. Conserv. Recycl. **151**, 104480 (2019)

Kochetkov, D.M., Larionova, V.A., Vukovic, D.B.: Entrepreneurial capacity of universities and its impact on regional economic growth. Economy of Region/Ekonomika Regiona **2**, 477–488 (2017). https://doi.org/10.17059/2017-2-13

Lenglet, F.: Can ESD reach the year 2020? Journal of Education for Sustainable Development 8 (2). Sage Publications, London, UK (2014)

Lillah, R., Viviers, S.: Does business education cultivate environmental citizenship? African Journal of Business Ethics, 8(1), 5–28 (2014). Retrieved from http://0-search.ebscohost.com.innopac.wits.ac.za/login.aspx?direct=true&db=bsu&AN=102127463&site=ehost-live&scope=site

Mitchell, A.S., Callaghan, C.W.: Building environmental sustainability into management theory and practice: An imperative in uncertain times? Paper presented at the British Academy of Management Conference, Birmingham (2019)

Mitchell, A.S., Lemon, M., Lambrechts, W.: Learning from the anthropocene: adaptive epistemology and complexity in strategic managerial thinking. Sustainability **12**(11), 4427 (2020)

Neubaum, D.O., Pagell, M., Drexler, J.J.A., McKee-Ryan, F.M., Larson, E.: Business education and its relationship to student personal moral philosophies and attitudes toward profits: an empirical response to critics. Academy of Management Learning & Education **8**(1), 9–24 (2009). https://doi.org/10.5465/AMLE.2009.37012176

Noe, R.A.: Employee training and development, 6th edn. McGraw-Hill, New York, USA (2013)

Organisation for Economic Co-operation and Development (OECD). Policy brief on making the most of the social economy's contribution to the circular economy. (Briefing paper) European Commission (2022). APO-316172

Prochaska, J.O., Norcross, J.C., Diclemente, C.C.: Changing for Good. HarperCollins Publishers, New York (1994)

Redmond, J., Walker, E.: Environmental education in small business: the owner-manager's perspective. Australian Journal of Environmental Education, 25 (2009)

Rockström, J., et al.: A safe operating space for humanity. Nature **461**, 472 (2009). https://doi.org/10.1038/461472a

Ryan, A., Tilbury, D.: Uncharted waters: voyages for Education for Sustainable Development in the higher education curriculum. Curric. J. **24**(2), 272 (2013)

Serrano-Bedia, A.-M., Perez-Perez, M.: Transition towards a circular economy: A review of the role of higher education as a key supporting stakeholder in Web of Science. Sustainable Production and Consumption **31**, 82–96 (2022). https://doi.org/10.1016/j.spc.2022.02.001

Sims, R.R.: Business ethics teaching: using conversational learning to build an effective classroom learning environment. J. Bus. Ethics **49**(2), 201–211 (2004). https://doi.org/10.1023/B:BUSI.0000015782.99051.d4

Sterling, S.: The future fit framework: an introductory guide to teaching and learning for sustainability in HE (Guide). J. Educ. Sustain. Dev. **7**(1), 134–135 (2014). https://doi.org/10.1177/0973408213495614b

Tilbury, D., Crawley, C., Berry, F.: Education About and For Sustainability in Australian Business Schools. Report prepared by the Australian Research Institute in Education for Sustainability (ARIES) and Arup Sustainability for the Australian Government Department of the Environment and Heritage (2005)

United Cities and Local Governments. Culture: Fourth Pillar of Sustainable Development. Mexico (2010)

United Nations. Transforming our world: the 2030 Agenda for Sustainable Development (2015)

UNECE. Empowering educators for a sustainable future: tools for policy and practice workshops on competences in education for SD. Geneva (2013)

UNESCO: Roadmap for implementing the global action programme on education for sustainable development. Paris, France: United Nations Educational, Scientific and Cultural Organization (2014)

Wiek, A., Keeler, L., Redman, C.: Key competencies in sustainability: a reference framework for academic program development. Sustain. Sci. **6**, 203–218 (2011). https://doi.org/10.1007/s11625-011-0132-6

World Commission on Environment and Development. Our Common Future, From One Earth to One World (1987)

Ye, F.Y., Yu, S.S., Leydesdorff, L.: The Triple Helix of university-industry-government relations at the country level and its dynamic evolution under the pressures of globalization. J. Am. Soc. Inform. Sci. Technol. **64**(11), 2317–2325 (2013). https://doi.org/10.1002/asi.22931

# Training and Skills Development for the Circular Economy in the Current Geopolitical Context: A Bottom-Up Design Focused on Community Need and Social Enterprise

Antonio Sánchez-Vázquez(✉), Alex Mifsud, and Chris Callaghan

Anglia Ruskin University, East Road, Cambridge CB1 1PT, UK
{antonio.sanchez-vazquez,alex.mifsud,chris.callaghan}@aru.ac.uk

**Abstract.** The rise of circular economic thinking in academic literature can be traced back to Boulding's work on open and closed systems in the 1960s. Since then, the Circular Economy (CE) has been developed as a model to facilitate environmentally sustainable production and consumption, as well as economic and social prosperity. Recent geopolitical destabilising events such as Covid-19, and the war in Ukraine, have further increased the urgency of finding practical solutions to the climate crisis. In this paper we will explore industrial transformation, and how it can best adapt to a more circular and greener landscape from the perspective of economic activity and social prosperity. Training, or retraining of the workforce with the new skills they will need must be targeted and part of a unifying strategy, locally, nationally, and ultimately, globally. We present a conceptual paper on this theme and present initial work carried out to co-design and deliver training to disadvantaged individuals; working with local authorities, community charities and social enterprises and focusing on the grassroots of the drive to promote and establish the system wide changes needed to shift from linear to circular economic practice.

**Keywords:** Circular economy · Sustainability · Public policy · Social enterprise

## 1 Geo-Political and Environmental Context

Environmental degradation now poses an existential threat to humankind (Mitchell et al., 2020). Global warming and increasing carbon dioxide (CO2) and other greenhouse gas emissions are leading to increased global temperatures (Trenberth et al., 2014). Drinking water pollution and accumulation of effluent and even pharmaceuticals in the water supply is increasing (Benotti et al., 2009) together with plastic waste in the planetary water systems (Jambeck et al., 2015). These, and other effects, have been described as the advent of the Anthropocene (Mitchell et al., 2020), the age of the human where modern industrial lifestyle has become the dominant threat to the planet and the environment.

Much scholarly work has sought to develop best practices to improve recycling, reuse, and to reengineer business models to embrace sustainability (Piscicelli et al., 2018).


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 351–360, 2023.
https://doi.org/10.1007/978-981-19-9205-6_34

Efforts have also been made to embed sustainability in public procurement (Rainville, 2021), the operation of clothing markets (Goworek et al., 2012), and in fashion (Goworek et al., 2020), lengthening product life cycles and slowing consumption (Cooper, 2005). Despite some progress in certain areas, over the past decade, there has been little progress towards systemic and systematic changes needed to address this existential threat. Some work suggests that businesses are starting to lose interest in the circular economy, as they deem it too hard to implement in practice (Kirchherr and van Santen 2019).

A failure to take a holistic ‘bottom-up’ approach to finding solutions may risk ineffective policies and targets failing due to the exclusion of the individuals and communities, whom it is vital to reach, as both producer and consumer in all economic models.

Developed countries have advanced on the back of environmental pollution and degradation and there is righteous indignation among developing countries who did not contribute to it, but now also abide by the limitations inherent in overcoming the challenges of global sustainable development. These tensions were palpable during the COP26 Summit in November 2021 (Reliefweb 2021) where leaders of the emerging and developing economies made powerful statements on climate injustice.

Of the increasingly more influential BRICS countries, Brazil in 2018 had a population of about 209 million, Russia 144 million, India 1.35 billion, China 1.39 billion, and South Africa 57.8 million, together comprising about 3.15 billion, or close to 42% of the world’s population. The USA, UK, France, and Germany have great influence geopolitically, and with the BRICs countries include about 3.694 billion, or 49% of the world’s population (WB, 2020). It might not be an exaggeration to suggest that geopolitical forces arising from these countries disproportionately shape global geopolitical and economic realities.

The current Ukraine war (Boungou and Yatié, 2022; Johannesson and Clowes, 2022) brings home an important message. We cannot assume that the goals and values of a small minority of the world’s population of developed countries are shared with those of BRICS and other developing counties. This assumption may be a particularly dangerous heuristic.

As part of their history, many developed countries experienced increasing nationalism, which led to World War II, a conflict between liberal values and nationalistic militarism. To what extent is nationalistic militarism an unavoidable stage in the development of leading powers as they approach an economically developed status? Are we experiencing a retreat from globalisation due to a rise in nationalism not seen since the 1930s? Some have argued that growth in globalisation has been slowing, from about the year 2000 onwards, with growth of economic globalisation negative for the first time this century in 2016, perhaps due to the forces of deindustrialisation (Callaghan, 2021). This is exemplified in the following text from Preston:

“Globalisation has been rolled back since the banking crisis of 2008, first by the banking regulation that followed, then by Trumpian and Brexit nationalism and mercantilism, then by Covid and now by the shock of war. The current dislocation of supply chains, especially for energy but much more broadly, means inflation will be much higher for longer- because businesses will speed up the shift in procurement of raw materials, energy, components, etc. to suppliers much closer to home. History may show that the definitive moment globalisation stalled was when China, India and South Africa all abstained on the United Nations vote condemning the invasion of Ukraine by Russia." (Preston 2022: 1).

Although Preston's perspective may be extreme and it is unlikely that the failure of China, India, and South Africa to join the vote to condemn the invasion of Ukraine represents the 'death of globalization', the implication of these global geopolitical events cannot be ignored. These events need to be understood within increases in indicators of global autocracy (Repucci and Slipowitz, 2022), as liberal democracy is also declining across the world.

One has to ask, to what extent are countries that are becoming increasingly autocratic, and autocratic countries, really incentivized to become sustainable, or to expend scarce resources on mitigating climate change they may feel they did not cause? Reshaping of geopolitical power relationships is a dynamic process, and elites can now more effectively manipulate and control populations using rapidly evolving technologies (Callaghan, 2018). We suggest here that Mode 2 knowledge creation is required, that focuses academic, industry, and governmental resources in a triple helix approach (Etzkowitz and Leydesdorff, 2000; Limoges et al., 1994). Although what we argue might be taken to be common knowledge, there seems to have been little progress to date at resolving the environmental crisis, which at this point is perhaps an existential threat (Mitchell and Callaghan, 2019).

Rapid diffusion of CE knowledge and skills might be urgently needed, to embed behaviour change, from the bottom up, into communities and populations and equip these with the necessary tools to address these urgent concerns. In this conceptual paper, we follow Reese's guidelines (Reese 2022), to make the case for this and will present initial work done as part of the EU Interreg France(channel)England funded project: BLUEPRINT to the Circular Economy (2020–2023). This looks at ways to promote a circular economy by integrating processes and practices, at the local level, and effect change with co-development and delivery of bespoke training for local government, social enterprises, and individuals. By focusing on these stakeholders, the project will aim to have the greatest impact at the community level, as well as drive change from the ground-up, towards a greener and more socially inclusive economy.

## 2 Sustainability and the Circular Economy

Given the global direction of travel towards an unsustainable planet, and a growing awareness of the crisis this entails, the world's leading economies now all recognise what has been the majority scientific view since the 1970s, that pollution generated by modern lifestyle and the industries that support it, are responsible for changing the planetary biosphere, leading to global warming, extreme weather events, ecological devastation, and mass species extinction (Jambeck et al., 2015). All these have been accelerating in the 21st century, leading to complex systemic changes on an unprecedented scale. These extremes also drive mass migration and take place in a world where the geopolitical system is out of step with the reality of a global environment and are potentially ineffective in reacting in the timescales needed (Bimpizas-pinis 2021). Additionally, the displacement of people due to environmental and/or political crises, fuels the far-right nationalist sentiment in western economies leading to more divisions in society, at a time when what is needed is more unity.

The release of greenhouse gasses, especially carbon dioxide, the majority from fossilised carbon, along with one of its by-products, the group of chemicals known as 'plastic' are two key factors contributing to the changing climate. The excess greenhouse gasses accelerate global warming, which changes the climate, and plastic pollution now affects all biosystems, and we have yet to fully understand the effects it has on living organisms. There are other factors, such as global industrial agricultural practices, and an absence of rules governing what should be 'universal resources' such as oxygen generation systems or the seas and oceans, and the need for finding circular economy policy solutions is urgent (Hartley 2020).

The current policy of reducing the planetary carbon footprint to net-zero by 2050 is ambitious and requires significant reductions, not only of the world's largest economies, but also that other, developing economies, adopt low carbon systems, and do not follow the route of large-scale industrial farming. Presently the legal commitment to net-zero has only been made by a few countries, while Brazil, India and China have made policy commitments (see Fig. 1). From the perspective of the climate crisis, the ongoing recovery from the SARS Covid-19 pandemic, the current geopolitical complexities of de-globalisation, the war in Ukraine, and energy and food insecurity, can act as powerful drivers to stimulate action towards a more green and circular economy (Alvis 2021), and re-boot to a global economic model based on sustainable goals and inclusive circular ways of thinking and working.

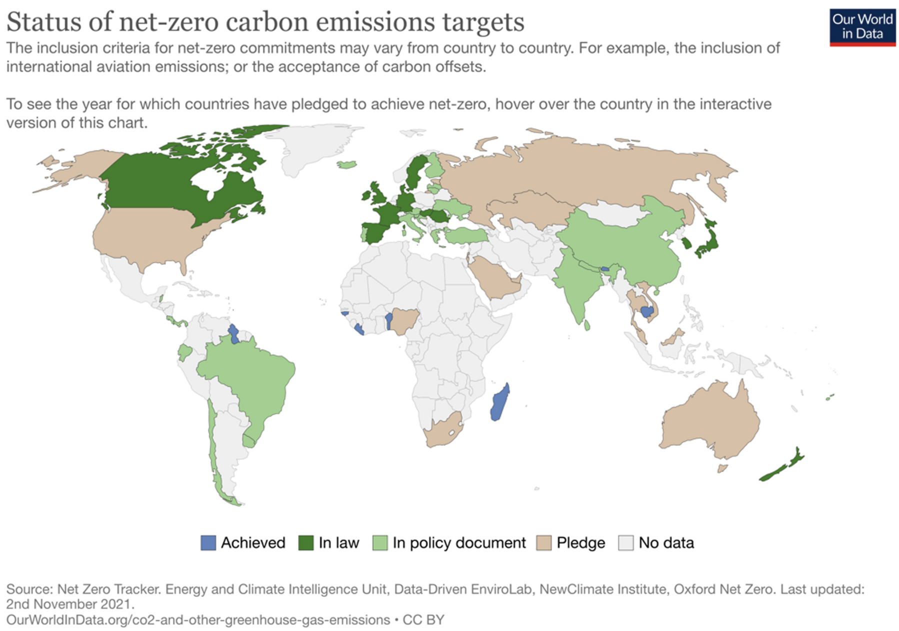



**Fig. 1.** Net-zero targets. Source Hannah Ritchie, Max Roser and Pablo Rosado (2020)

Since the rise of the concept 'the circular economy' it has been used as an umbrella term with no definitive definition. As a concept it embraces elements of economics, sustainability, ecology, business modelling, behavioural sciences, politics, and policy. From a practical perspective it brings all these together to focus the realisation that there is an urgent need to change the system, and a call to action if we wish to avoid the consequences of most activities that make up modern global systems of consumption and resource transformation (Padilla 2020).

This move towards a circular economy and a more sustainable future will require significant changes across the industrial spectrum. New sectors will emerge, old ones will disappear, and new markets and supply-chains be established to replace the old ones. This will require that a large part of the adult workforce be re-trained for the new occupations. The effect this will have on the labour force will be different for different regions and industries. Without a better understanding and a recognised standard classification of the circularity of industries, or a central strategy and inherently connected policies, training programmes may not align with the industrial sector's needs, or those of the workforce that require the training. It remains unclear how the changing climate will affect the labour market, or how a move towards a circular economic model will take place in practice (Martinez 2010). Moreover, while the need for better training and education has been recognised as a key factor in this transition (ibid), so far little has been established in the way of policy and practice that we can say are having an effect at the global scale. Indeed, despite decades of academic work on the circular economy, we have yet to find any evidence that it is a realistic and practically sustainable alternative to current linear economic models (Padilla 2020).

## 3 Transformation of Industry, Employment, and Society

While many industrially polluting jobs will disappear or be transformed, the move towards a less polluting, greener, circular economy, will also generate new employment and the establishment of a 'greener' labour market, which will be needed to prevent unemployment in those regions affected. For this transformation to be positive and resilient, we need a holistic and whole systems view of the industrial and social components of all sectors. We must especially consider physical and human geography, to ensure that any policies are targeted to promote efficiency and effectiveness so as to accelerate the process. If we wish to transform the most polluting industries and retrain and reskill their workforces, we will need to ensure that we really understand the industrial landscape and what skills and training are needed, as well as how and where these can be delivered to have the most effect in the shortest time.

Work has been carried out that focuses on aligning skills gaps with vocational education and training (Brown et al 2022), but the policy recommendations they suggest appear unrealistic in practice as they do not target specific industries with specific training and may not have an effect fast enough to be of value. At best, they risk becoming yet another series of potentially good policies, which were never applied, and at worsted, they fail to actually address the problems/challenges they were designed to solve (Hartley 2020).

### 3.1 Key Factors Influencing Transformation

Kapernaiou (2020) highlighted some of the key factors that may affect this transformation, these were focused on the UK market, and the creation of systems that would better allow us to understand, the geography, workforce demographic, and level of sustainable/circular/green credentials of industry. Merli (2018) also focus on the importance of developing a strategy to integrate social and economic dynamics and administrative processes with new models of consumer behaviour and product design. We expand on their work and explore options to suggest some of the vital actions necessary to achieve and effective transformation towards a circular economy.

The following propositions are made for areas where we need to focus on linking the intangible (social) and tangible (material) components of an overarching strategy. Perhaps, most importantly, these need to include the bottom-up perspective of the labour force that powers industry, and the top-down view of legal and regulatory policy frameworks, joined by strategic cohesion across sectors, regions, that foster sustainable international trade.

1. We must establish comparable metrics that can allow an understanding of how green/circular an industry/business is. While these must include material factors, waste and pollution, importantly it must include social, and human factors that make up the systems.
2. We must develop tools that give a better understanding of how existing skills map onto potential circular job skills. This will ensure that training is targeted to where it will be the most effective and make the transition as easy as possible for the workforce, and guide industrial development. This was not done when the mining industry was dismantled in the UK in the 1980, to disastrous effect (Murry 2005).
3. To ensure levelling up and that jobs and skills are developed in the areas that most need them, we must have an agreed policy and strategic process to guide re-mapping of the industrial landscape and ensure that we target training specific to different geographical areas and sectors, and different demographics and skill levels. Retraining and reskilling will need to be inclusive of the whole work force, especially targeting those individuals who are in most need and are most likely to be excluded (i.e., disadvantaged workers, or youths).
4. We must develop inclusive strategies that transform industry and the economy from the top-down, and from the bottom-up (or from the outside-in and the inside-out). As well as the need for a joined-up policy at all levels (international, national, and local), to promote a more circular and social economy globally, which will also require that individuals and communities who are highly motivated and driven by local and social concerns are included as part of the solution. Social Enterprise is more likely to effect change in individuals and communities at a local level and promote a tangible behavioural change towards more circular and socially just business models. And, to society in general.

### 3.2 Targeting Training and Skills Development for Individuals Based on Local Factors, Community Need and Social Enterprise: The BLUEPRINT Project

The transition to a CE in Europe is estimated to be worth €1.8 trillion a year by 2030 (Ellen MacArthur Foundation 2018). Yet, 'only limited progress has been accomplished so far regarding the CE's implementation' in the EU (Kirchherr 2018) and is 'little implemented in practice' (Ritzen 2017). McKinsey (2015) claim that this is due to 'non-optimal public sector and policy makers decisions. If policy makers do not address this issue, there could be substantial shortages of workers with the right sills to support sustainable growth and job opportunities that will be created through the CE.

The BLUEPRINT Project aims to promote employment and co-create new training programmes to reskill individuals for CE economy practices (i.e., better recycling, reverse logistics and secondary markets). These will target individuals most at risk of economic exclusion by developing a strategic framework that enables local authorities, social enterprise, and communities to accelerate the transition and transformation to a circular economy and meet among others, the EU target of raising municipal waste recycling rates to 65% by 2035. The project has focused on the issue of training and skills development from the perspective of the individual at the community level, and for this reason has worked with social enterprises and community interest groups to develop bespoke training that can be delivered to them and promote change at the grassroots and community level, which can then filter upwards towards the larger policy initiatives that are also driving towards a more sustainable world.

The project is also working to deliver the training with local authorities to develop the necessary policy and processes to reach those members of the community that are in most need of training and support them with the skills they need to secure work in the circular economy sector. Local councils are best placed to understand the needs of their areas and communities and ensure that the training will have a greater reach and more chance of reaching more members of the community. By addressing the training and skill development needs of individuals and communities directly, we can increase their effect at the base/center of the circular economy, the consumer. This will serve to diffuse the necessary skills to work in the circular economy, but it is also hoped that it will lead to more consumers living more sustainably.

### 3.3 Future Challenges for a Circular Economy to Drive Sustainable and Socially Just Development

Key challenges focus on data and information management, the use of digital technologies and aligning commensurate policy with practice. In his cornerstone paper, 'The Economics of the Coming Spaceship Earth' Boulding (1966), looked at previous work on biological models of open and closed systems and formed the basis of what we now call the circular economy, with its open and closed loops and material and energy flow models based on mimicking the cycles of life. Boulding also introduced the concept of open and closed information systems, which have not yet been taken up by the circular economy movement, and could provide insight into better use of data.

Developing, sustainable digital technologies such as: Industrial Technology 4.0, Big Data, Data Analytics the Internet of Things, AI, and machine learning, Blockchain, etc.(Kahn 2022); and the power of social media and fake news to shape our outlook, these are important areas that can guide and promote a CE and need further expansion.

As well as matching policy commitment to delivery of training/reskilling, the sector is underfunded and in need of investment. To date there has been varied success in developing greener jobs, depending on which sector and which country, but overall, very few new green jobs have been created. Monitoring of sectors, skills and training remains ad-hoc and unfocused and underfunded. Improved data structures are required to allow to richer data to focus on a system wide solution (Faso 2010).

## 4 Conclusion

Alternative education and training routes (i.e., charities, adult community learning centres, social enterprises) can offer more effective and cheaper alternatives to higher education or training. Inclusive training must be developed with those organisations to target the specific skills gaps and needs of local communities and individuals, as well as industrial sectors more widely. New skills will be vital, to remap existing occupations, and drive the extensive transformation the shift to a more sustainable economic model will bring. New forms of accreditation will also need to be established, and certification standards will also need to be developed.

The BLUEPRINT project is piloting this new model of inclusive retraining and reskilling, at the community level working with social actors and local stakeholders. Good leadership, at national and international level will also be needed to marry this with higher level policy and sector wide transformation, to ensure that the bottom-up and top down, do indeed meet in the middle, and strategic policies become more targeted and effective for the essential transition towards a greener and more sustainable circular economy. Institutional and organisational, as well as community and individual cooperation and collaboration are essential to achieve this vital transformation in time.

Given the importance of addressing the issue of how we effectivity move towards greater sustainability, we are indeed in need of answers to some of the big questions we have raised. Even if Western European and other liberal democracies can actuate strategies and policies that do support sustainable economic models, they will not be enough without buy-in from the worlds most populated economies. The current geopolitical context in which we find ourselves in shows us how rapidly things can change. System wide strategic thinking does not seem able to operate at the speeds necessary to be effective, and we propose to address the problem from the bottom-up and work to promote action from the individual, community, and societal levels to attempt to change the way we live, work, and do business.

The authors wish to acknowledge BLUEPRINT to a Circular Economy, which is an Interreg VA France (Channel)England project No206.

## References

Alvis, S., Avison, Z.: Levelling up through circular economy jobs, Green Alliance (2021)

Bianchi, G., Pisiotis, U., Cabrera Giraldez, M.: GreenComp The European sustainability competence framework. In: Punie, Y., Bacigalupo, M. (eds.) EUR 30955 EN. Publications Office of the European Union, Luxembourg (2022)

Bimpizas-Pinis, M., Bozhinovska, E., Genovese, A., et al.: Is efficiency enough for circular economy? Resources, Conservation and Recycling 167 (2021)

Boulding, K.E.: The Economics of the Coming Spaceship Earth. In: Jarrett, H. (ed.) Environmental Quality in a Growing Economy, pp. 3–14. Resources for the Future/Johns Hopkins University Press, Baltimore, MD (1966)

Brown, E.G., Haigh, L., Schroder, A.: Closing the skills gap: vocational education and training for the circular economy Report Circle Economy 2022
Faso, B.: Skills for a greener future: Challenges and enabling factors to achieve a just transition. International Labour Office 2010
Hannah, R., Max, R., Pablo, R.: $CO_2$ and Greenhouse Gas Emissions. Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions, last accessed 27 May 2022
Hartley, K., van Santen, R., Kirchherr, J.: Policies for transitioning towards a circular economy: Expectations from the European Union (EU). Resources, Conservation and Recycling. **155**, 104634 (2020 Apr 1)
Jambeck, J.R., et al.: Plastic waste inputs from land into the ocean. Science **347**(6223), 768–771 (2015)
Johannesson, J., Clowes, D.: Energy Resources and Markets-Perspectives on the Russia-Ukraine War. European Review **30**(1), 4–23 (2022)
Khan, S.A., Shah, A.S., Yu, Z., Tanveer, M.: A systematic literature review on circular economy practices: challenges, opportunities and future trends. Journal of Entrepreneurship in Emerging Economies (2022). Ahead of print: https://doi.org/10.1108/JEEE-09-2021-0349
Kirchherr, J., et al.: Barriers to the circular economy: evidence from the european union (EU). Ecol. Econ. **150**, 264–272 (2018)
Kirchherr, J., van Santen, R.: Research on the circular economy: a critique of the field. Resour. Conserv. Recycl. 151 (2019)
Limoges, C., Scott, P., Schwartzman, S., Nowotny, H., Gibbons, M.: The new production of knowledge: The dynamics of science and research in contemporary societies. Sage, London (1994)
Martinez-Fernandez, C., Hinojosa, C., Miranda, G.: Greening jobs and skills: labour market implications of addressing climate change OECD LEED Programme 2010
McKinsey report: Urban mobility at a tipping point, McKinsey Center for Business and Environment August 2015, McKinsey & Company. https://www.mckinsey.com/business-functions/sustainability/our-insights/urban-mobility-at-a-tipping-point accessed 30 May 2022
Merli, R., Preziosi, M., Acampora, A.: How do scholars approach the circular economy? A systematic literature review. Journal of cleaner production **178**, 703–22 (2018 Mar 20)
Mitchell, A.S., Callaghan, C.W.: Building environmental sustainability into management theory and practice: An imperative in uncertain times? Paper presented at the British Academy of Management Conference, Birmingham (2019)
Mitchell, A.S., Lemon, M., Lambrechts, W.: Learning from the anthropocene: adaptive epistemology and complexity in strategic managerial thinking. Sustainability **12**(11), 4427 (2020)
Murray, R., Baldwin, J., Ridgway, K., Winder, B.: Socio-economic decline and adaptation: South Yorkshire's former coalfields. Local economy. **20**(4), 344–59 (2005 Nov)
Padilla-Rivera, A., Russo-Garrido, S., Merveille, N.: Addressing the social aspects of a circular economy: A systematic literature review. Sustainability **12**(19), 7912 (2020)
Piscicelli, L., Ludden, G.D.S., Cooper, T.: What makes a sustainable business model successful? An empirical comparison of two peer-to-peer goods-sharing platforms. J. Clean. Prod. **172**, 4580–4591 (2018)
Preston, R.: (Producer). Preston: How Putin has killed globalisation and what it means for us. itv News 22 May 2022
Rainville, D.A.: Stimulating a more circular economy through public procurement: roles and dynamics of intermediation. Res. Policy **50**(4), 104193 (2021)
Reese, S.D.: Writing the Conceptual Article: A Practical Guide. Digital Journalism, Ahead-of-print, 1-16 (2022). https://doi.org/10.1080/21670811.2021.2009353

Reliefweb news, https://reliefweb.int/report/world/cop26-failed-world-s-poorest, last accessed 01 June 2022
Repucci, S., Slipowitz, A.: The Global Expansion of Authoritarian Rule. https://freedomhouse.org/sites/default/files/2022-02/FIW_2022_PDF_Booklet_Digital_Final_Web.pdf. accessed 31 May 2022
Ritzén, S., Sandström, G.Ö.: Barriers to the circular economy—Integration of perspectives and domains. Procedia CIRP **64**, 7–12 (2017)
Trenberth, K.E., et al.: Global warming and changes in drought. Nat. Clim. Chang. **4**(1), 17–22 (2014)
WB. World Bank World Development Indicators. https://databank.worldbank.org/source/world-development-indicators. accessed 31 May 2022

# Industrial Symbiosis and Industry 4.0: Literature Review and Research Steps Toward Sustainability

Valentina Ventura, Marco Bortolini, and Francesco Gabriele Galizia(✉)

Department of Industrial Engineering, University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy
francesco.galizia3@unibo.it

**Abstract.** The recognition of Industry 4.0 (I4.0) technologies as enablers of Circular Economy (CE) is a debated topic throughout the last decade. Material flows and operations within circular cross-industry networks require information sharing platforms and supporting digital tools to improve resource optimisation and to aim at CE principles. As a branch of CE, Industrial Symbiosis (IS) connects traditionally separated entities for sharing and exchanging by-products, energy, information and know-how. Practical implementations of IS are still limited. Several factors currently hamper the implementation of IS exchanges, i.e., technical, managerial, legislative, social, and I4.0 technologies, especially sensors, IoT and data analytics, can contribute to address them. However, in current literature few studies explore this promising tandem. According to this vision, this paper presents an updated review of the literature about the concepts of "Industry 4.0" and "Industrial Symbiosis", focusing, firstly, on the analysis of the authors keywords, and then, on the identification of methods and applications used. Finally, potential areas of interest for future agendas of researchers and practitioners in this field are proposed.

**Keywords:** Industrial symbiosis · Industry 4.0 · Literature review

## 1 Introduction

Digitalisation and sustainability are two of the most debated topics driving international discussions during the last decades. Although they have been commonly investigated as separated research themes, several synergies can be identified by overlapping them [1]. Within an industrial perspective, the digitalisation of production systems is associated to Industry 4.0 (I4.0), whilst sustainability suggests a more efficient use of natural resources and closed loop supply chains, related to principles regulating the so-called Circular Economy (CE) [2].

The term "Industrie 4.0" emerged in 2011 into a high-tech strategy project of German government regarding manufacturing computerisation, and then it was publicly introduced during the Hannover Fair. I4.0 transforms traditional production systems with the


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 361–369, 2023.
https://doi.org/10.1007/978-981-19-9205-6_35

use of advanced digital technologies and Internet, aiming at the full automation and digitalisation. In 2015 the Boston Consulting Group recognises nine enabling technologies of I4.0: big data and analytics, autonomous robots, additive manufacturing, simulation, augmented and virtual reality, horizontal and vertical system integration, the Industrial Internet of Things (IoT), cloud, and cyber-security [3, 4].

On the other hand, overcoming the conventional "take-make-dispose" industrial paradigm, the CE concept promotes the closing of resources loops by aiming at zero waste production and harmful emissions reduction, extending the life cycle of a product or a service. Instead of thinking to a finite supply of resources, products and components are redesigned and rethought to adopt a returned and renewed culture, and to ease disassembly and recycling after their first usage [5].

To implement CE principles, Industrial Symbiosis (IS) can positively contribute to optimise the use of material and energy resources within a specific geographical area. It engages distinct organisations in an industrial network where by-products and outputs of a company represent potential inputs and raw materials for another business [6]. Allowing companies and entities that traditionally are separated to cooperate by sharing resources, sustainability is enhanced in terms of environmental, economic and social benefits [7]. However, the practical implementation of an IS network is hampered by several factors. First, taking part in an IS network (ISN) is an investment of financial resources and time. Then, a variety of cultural, managerial, technological, legislative issues affects decision making [8]. In addition, the efficient simultaneous management of physical and informational flows in cross-industry networks requires the integration of different skills. Industry 4.0 technologies, especially sensors, IoT and data analytics, are expected to boost the efficiency of circular material flows by data [9].

The aim of this paper is to present an updated literature review on the merging of the topics of IS and I4.0. According to this background, the reminder of this paper is structured as follows: the next Sect. 2 analyses the authors keywords and targets addressed, whilst Sect. 3 discusses the methodologies and applications. Finally, Sect. 4 draws conclusions and potential research steps.

## 2 Database Creation, Keywords Analysis and Research Targets

The review process focused on titles, abstracts, and author keywords by using Scopus and Web of Science as sources of scientific papers. First, a keyword search was conducted in Scopus. Second, Web of Science was consulted as a renowned database for assuring the consistency of the analysis. During the article screening, search strings contained only the two main terms: "Industry 4.0" and "Industrial Symbiosis". The analysis allowed finding 21 articles and collecting data about title, authors, years, keywords, and research targets. The analysis included relevant contributions published after 2016. Nevertheless, all the papers are dated from 2017 onward, confirming the novelty of the research. The subject areas cover engineering, environmental science, business management and accounting, and computer science. While the number of studies addressing CE and I4.0, jointly, is wide, few explore the link between IS, rose as a branch of CE, and I4.0 [5].

The retrieved papers are analysed by authors keywords to comprehend the synergies between IS, I4.0 and other related topics. Table 1 shows the most frequently used keywords, present in at least two papers within the selected set of articles.

**Table 1.** Author keywords (present in at least two papers out of the total).

| | | Author Keywords | | | | | | | | | | Ref |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Author(s) | Year | I4.0 | I.S | C.E | Sust.Manuf | Sustainab | A.I | C.B.M | Eco Eff | Ind.Ecol | Waste.M | |
| Ferrera et al | 2017 | X | X | | X | | | | X | | | [10] |
| Baptista et al | 2018 | | | | | | | | X | | | [11] |
| Tseng et al | 2018 | X | | X | | | | | | | | [12] |
| Garcia-Muiña et al | 2019 | X | X | X | | X | | X | | | | [13] |
| Hertwig et al | 2019 | | X | | | | | | | | | [14] |
| Kalyan et al | 2019 | | X | | | | | | | X | X | [15] |
| Kerdlap et al | 2019 | X | X | | X | | | | | | | [16] |
| Naderi et al | 2019 | X | | | X | | X | | | | | [17] |
| Colla et al | 2020 | X | | | | | X | | | | | [18] |
| Gurjanov et al | 2020 | | X | X | | | | | | | | [19] |
| Ponis | 2020 | | | X | | | | X | | X | | [8] |
| Scafà et al | 2020 | X | X | | | | | | | | | [20] |
| Cohen and Gil | 2021 | X | | X | | | | | | | X | [21] |
| Jamwal et al | 2021 | X | | | X | X | | | | | | [22] |
| Järvenpää et al | 2021 | X | X | X | | | | | | | | [9] |
| Mendez-Alva et al | 2021 | | X | X | | X | | | | | | [23] |
| Norouzi et al | 2021 | | | X | | | | | | | | [24] |
| Pizzi et al | 2021 | | | X | | | | | | | | [25] |
| Pyakurel and Wright | 2021 | | X | | | | | | | | | [26] |
| Cappelletti et al | 2022 | X | | X | | | | | | | | [27] |
| Chari et al | 2022 | X | X | X | | | | | | | | [28] |
| Total | | 12 | 11 | 11 | 4 | 3 | 2 | 2 | 2 | 2 | 2 | 21 |

The sparsity of the keywords distribution in Table 1 demonstrates the lack of established commons streams under investigation. The keywords "Industry 4.0", "Industrial Symbiosis" and "Circular Economy" are the most widely adopted by the authors, with a frequency of 12, 11 and 11 respectively, out of a total of 21 papers. A Pareto chart is used to order by occurrence all the keywords of the retrieved contributions (Fig. 1).

Starting from this analysis, the selected articles are examined by considering how authors address the topics associated to the three most used keywords (I4.0, IS, CE) and what common threads emerge in papers research targets.

## 2.1 Shared Features

The contributions jointly considering the three most adopted keywords, i.e., I4.0, IS, CE, are by Garcia-Muiña et al. [13], Järvenpää et al. [9] and Chari et al. [28]. Garcia-Muiña et al. [13] tested eco-design phase and IoT technologies in the ceramic tile production for promoting a circular business model as a tool of competitiveness in enterprises. Eco-design allowed to assess different industrial solutions and to forecast their performance by an environmental, socio-economic and technological perspective. Järvenpää et al. [9] explored the information sharing related to IS material flow and how I4.0 can facilitate waste or by-product flows. A case study composed by three sub-cases, three materials and eight Finnish companies was used for conducting qualitative interviews. The research revealed difficulties in investing in I4.0 technologies compared to the information value, and it suggested that significant benefits can be achieved considering the whole network of actors. Finally, Chari et al. [28] conducted qualitative research to assess how dynamic capabilities (DCs) enable manufacturing supply chains to build resilience and transition to CE. Three steps constituted the research process: a literature review, with the keywords "resilience", "Circular Economy", "Industrial Symbiosis", "DCs" and "capabilities", the participation of a European project to investigate the potential of IS in Europe, and interviews to experts. The role of I4.0 in the development of DCs was also investigated since it emerged from the review.

Other relevant contributions about I4.0 and IS are proposed by Tseng et al. [12], Colla et al. [18], Ponis [8] and Pyakurel and Wright [26]. Tseng et al. [12] discussed the mitigation of the complexity of cross-industry networks in multiple supply chains with I4.0 tools, including data-driven methods and big-data analysis. In this context, research opportunities included the identification of sustainability gains from empirical assessment of I4.0, the optimisation of IS practices through mathematical models for providing decision-making support, data-driven analysis among industrial networks, the development of universally applicable metrics for IS and big-data driven analysis for the benchmarking of different IS parameters. Colla et al. [18] presented a set of application examples in the steel industry with the aim of implementing digital enablers for CE and IS solutions, such as big data techniques, Machine Learning (ML) and Artificial Intelligence (AI). The heterogeneity of data sources, the different available volumes and the unpredictable frequency of data sampling require advanced decision-methods to support managers and to improve the environmental footprint of production processes. Ponis [8] introduced an innovative business model supported by a B2B marketplace based on blockchain technology to mitigate IS barriers and to enable the creation of symbiotic relationships among cross-sectoral manufacturing firms in Greece, i.e., ISN, Industrial Symbiosis Network. In this context, blockchain acts both as a trust mechanism and an exchange platform. The model has technical and social limitations due to the lack of trusts among participants and the technology adoption. Pyakurel and Wright [26] proposed a framework and a methodology for the implementation of energy and resources cooperation combining related topics of IS, sharing economy and CE. Authors highlighted the significance of potential applications of blockchain technology and I4.0 in coordination and information sharing, and in enhancing trust among IS entities.

The performed analysis reveals that the main issues faced concern the management of information flows and the analysis of large amounts of heterogeneous data. The branch of I4.0 technologies related to Information Technology (IT), i.e., AI, big data and analytics, IoT, cloud, and cyber-security, is the most debated for addressing IS networks complexity. Frameworks and procedures that test I4.0 technologies especially within real industrial cases and circular supply chains cover most of the scientific papers.

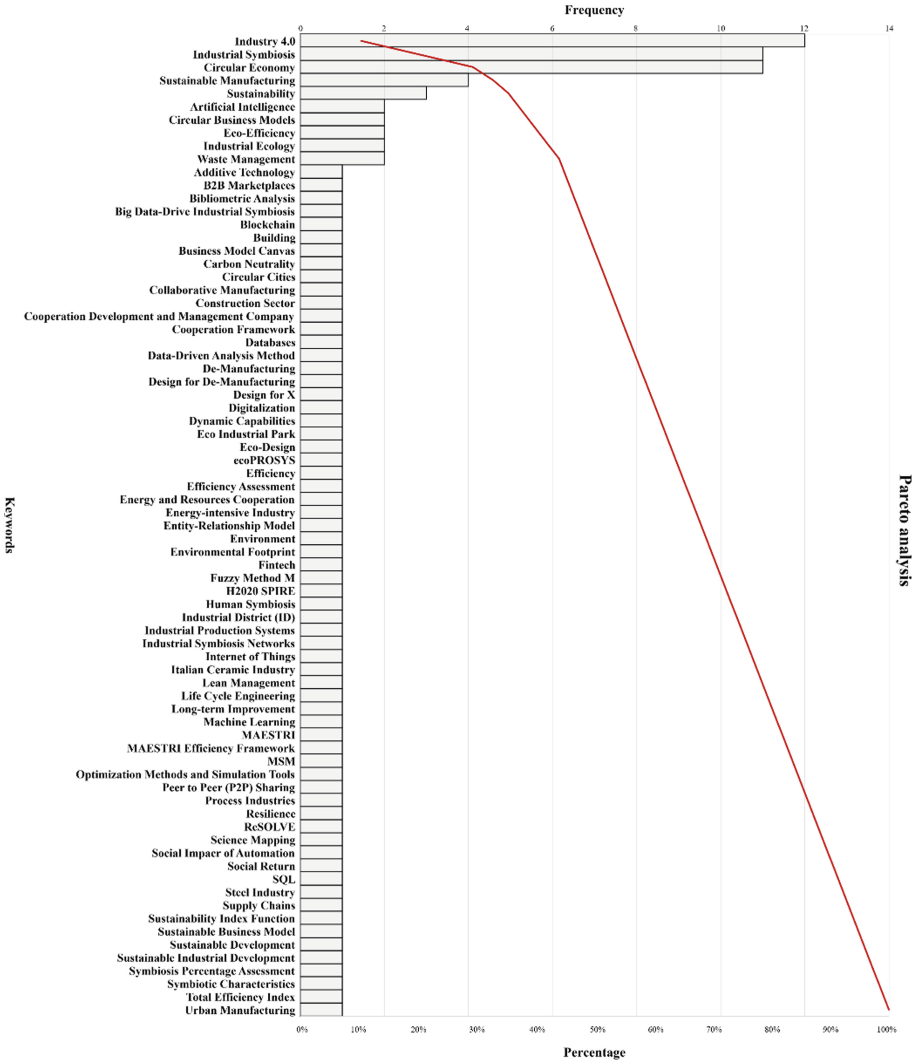



**Fig. 1.** Pareto analysis of the keywords frequency.

Next section will explore more in depth the methods and applications of the retrieved contributions.

## 3 Methodologies and Applications

This section is devoted to analysing papers by methodology adopted and by possible applications. Table 2 illustrates a classification of the articles according to the methodologies and the type of application used. Methods are divided into literature review, frameworks and procedures and algorithms. Frameworks are qualitative methodologies represented by logical schemes, such as conceptual or operative. Procedures and algorithms include quantitative methodologies, optimal or heuristic, consisting in a finite sequence of instructions to achieve a result. About the applications, illustrative examples and industrial real case studies are considered.

**Table 2.** Contributions classification by methodology and application.

| Author(s) | Year | Paper methodology | | | Application | | Ref |
|---|---|---|---|---|---|---|---|
| | | Review | Frame-work | Procedures & Algorithms | Illustrative example | Industrial case study | |
| Ferrera et al | 2017 | | X | | | | [10] |
| Baptista et al | 2018 | | X | | | X | [11] |
| Tseng et al | 2018 | X | | | | | [12] |
| Garcia-Muiña et al | 2019 | | | X | | X | [13] |
| Hertwig et al | 2019 | | | X | | X | [14] |
| Kalyan et al | 2019 | | | X | | X | [15] |
| Kerdlap et al | 2019 | X | X | | | X | [16] |
| Naderi et al | 2019 | | | X | | X | [17] |
| Colla et al | 2020 | X | | | | | [18] |
| Gurjanov et al | 2020 | | X | | X | | [19] |
| Ponis | 2020 | | X | | | | [8] |
| Scafà et al | 2020 | X | | | | | [20] |
| Cohen and Gil | 2021 | | X | | X | | [21] |
| Jamwal et al | 2021 | X | | | | | [22] |
| Järvenpää et al | 2021 | | | X | | X | [9] |
| Mendez-Alva et al | 2021 | | | X | | X | [23] |
| Norouzi et al | 2021 | X | | | | | [24] |
| Pizzi et al | 2021 | | X | | | | [25] |
| Pyakurel and Wright | 2021 | | X | X | | | [26] |
| Cappelletti et al | 2022 | X | | | | | [27] |
| Chari et al | 2022 | | X | | | X | [28] |
| Total | | 7 | 9 | 7 | 2 | 9 | |

As shown in Table 2, the use of qualitative approaches within paper methodologies, i.e., literature reviews and frameworks, exceeds the use of quantitative ones, i.e., procedures and algorithms. In addition, by analysing scientific methods, mathematical models, e.g., optimisation models, still constitute a small portion of the total. Regarding applications, industrial cases represent the majority compared to illustrative examples. The validation of several methods and procedures in real business contexts is very significant and promising for the future development of the analysed research topic in Academia and Industry.

## 4 Conclusions and Next Steps

Nowadays, digitalisation and sustainability represent two of the most debated topics in Academia and Industry. Within industrial contexts, the opportunities provided by Industry 4.0 (I4.0) technologies can address environmental challenges. Material flows and operations within circular cross-industry networks, i.e., Industrial Symbiosis (IS), require information sharing platforms and supporting digital tools to improve resource optimisation and to aim at Circular Economy (CE) principles.

The aim of this paper is to present an updated literature review on the merging of the concepts of IS and I4.0. The review allowed to retrieve 21 scientific papers. The analysis of the papers pointed out mainly the variety of contributions by keywords, methodologies and applications. This emphasises bibliometric evidence of the sparsity of scientific literature and the lack of common threads. The main issues faced concern information flow management and data analysis for decision-making support within IS contexts. AI, big data and analytics, IoT, cloud, and cyber-security are the most debated I4.0 technologies for addressing IS networks complexity. Qualitative frameworks are preferred, whilst regarding applications, methodologies are tested and validated through industrial case studies.

The limitations of the study concern the restricted set of keywords selected. There may be related articles that the review does not cover, but the extension of the research to other keyworks would have expose to the risk of including articles not strictly related to I4.0 and IS. A possible future research development will comprehend related keywords for both IS, such as CE, waste management, circular supply chain networks, and I4.0, including the key enabling technologies.

Given the evident potential of I4.0 technologies within IS, future research agendas are encouraged to deeply investigate these two topics from an applied perspective, also implementing quantitative approaches. A "smart" IS is the target to achieve, supported by digital platform based on I4.0 technologies, e.g., blockchain or cloud computing, and that leverage the energy and resources cooperation among firms or entities to reduce emissions and optimise the circular networks.

## References

1. 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)

2. Rajput, S., Singh, S.P.: Connecting circular economy and industry 4.0. Int. J. Info. Manage. **49**, 98–113 (2019)
3. Bortolini, M., Calabrese, F., Galizia, F.G., Mora, C., Ventura, V.: Industry 4.0 Technologies: A Cross-sector Industry-Based Analysis. In: Proceedings of the International Conference on Sustainable Design and Manufacturing 2021, KES-SDM, vol 262, pp. 140–148. Springer, Singapore (2022)
4. Rüßmann, M., et al.: Industry 4.0: The future of productivity and growth in manufacturing industries. Boston consulting group **9**(1), 54–89 (2015)
5. Ellen MacArthur Foundation, https://ellenmacarthurfoundation.org/, last accessed 16 May 2022
6. Chertow, M.R.: Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy Env. **25**(1), 313–337 (2000)
7. Neves, A., Godina, R., Azevedo, S.G., Matias, J.C.: A comprehensive review of industrial symbiosis. J. Clean. Prod. **247**, 119113 (2020)
8. Ponis, S.: Industrial Symbiosis Networks in Greece: Utilising the Power of Blockchain-based B2B Marketplaces. The Journal of The British Blockchain Association, 18206 (2020)
9. Järvenpää, A.M., Salminen, V., Kantola, J.: Industrial Symbiosis, Circular Economy and Industry 4.0–A Case Study in Finland. Management and Production Engineering Review **12**(4), 111–121 (2021)
10. Ferrera, E., et al.: Toward Industry 4.0: efficient and sustainable manufacturing leveraging MAESTRI total efficiency framework. In: International Conference on Sustainable Design and Manufacturing, pp. 624–633, Springer, Cham (2017)
11. Baptista, A.J., Lourenço, E.J., Silva, E.J., Estrela, M.A., Peças, P.: MAESTRI Efficiency Framework: The concept supporting the Total Efficiency Index. Application case study in the metalworking sector. Procedia CIRP **69**, pp. 318–323 (2018)
12. Tseng, M.L., Tan, R.R., Chiu, A.S., Chien, C.F., Kuo, T.C.: Circular economy meets industry 4.0: Can big data drive industrial symbiosis?. Resources, conservation and recycling **131**, 146–147 (2018)
13. Garcia-Muiña, F.E., et al.: Identifying the equilibrium point between sustainability goals and circular economy practices in an Industry 4.0 manufacturing context using eco-design. Social sciences **8**(8), 241 (2019)
14. Hertwig, M., Lentes, J., Zimmermann, N., Dangelmaier, M.: Stuttgart Region—Sustainable Industrialization in Stuttgart Metropolitan Region. In: Vinod Kumar, T.M. (ed.) Smart Metropolitan Regional Development. ACHS, pp. 175–236. Springer, Singapore (2019). https://doi.org/10.1007/978-981-10-8588-8_3
15. Kalyan, C., Abhirama, T., Mohammed, N.R., Aravind Raj, S., Jayakrishna, K.: Measuring Industrial Symbiosis Index Using Multi-Grade Fuzzy Approach. In: Hiremath, S.S., Shanmugam, N.S., Bapu, B.R.R. (eds.) Advances in Manufacturing Technology. LNME, pp. 49–58. Springer, Singapore (2019). https://doi.org/10.1007/978-981-13-6374-0_7
16. 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. Recycl. **151**, 104438 (2019)
17. Naderi, M., Ares, E., Peláez, G., Prieto, D., Araújo, M.: Sustainable operations management for industry 4.0 and its social return. IFAC-PapersOnLine **52**(13), 457–462 (2019)
18. Colla, V., Pietrosanti, C., Malfa, E., Peters, K.: Environment 4.0: How digitalization and machine learning can improve the environmental footprint of the steel production processes. Matériaux & Techniques **108**(5–6), 507 (2020)
19. Gurjanov, A.V., Shukalov, A.V., Zharinov, I.O.: Techno-sphere safety of non-waste production. In: IOP Conference Series: Earth and Environmental Science, vol. 548, No. 5, p. 052032. IOP Publishing (2020)

20. Scafà, M., Marconi, M., Germani, M.: A critical review of symbiosis approaches in the context of Industry 4.0. Journal of Computational Design and Engineering **7**(3), 269–278 (2020)
21. Cohen, J., Gil, J.: An entity-relationship model of the flow of waste and resources in city-regions: Improving knowledge management for the circular economy. Resources, Conservation & Recycling Advances **12**, 200058 (2021)
22. Jamwal, A., Agrawal, R., Sharma, M.: Life cycle engineering: past, present, and future. In: Sustainable Manufacturing, pp. 313–338. Elsevier (2021)
23. Mendez-Alva, F., Cervo, H., Krese, G., van Eetvelde, G.: Industrial symbiosis profiles in energy-intensive industries: Sectoral insights from open databases. J. Clean. Prod. **314**, 128031 (2021)
24. Norouzi, M., Chafer, M., Cabeza, L.F., Jiménez, L., Boer, D.: Circular economy in the building and construction sector: A scientific evolution analysis. Journal of Building Engineering **44**, 102704 (2021)
25. Pizzi, S., Corbo, L., Caputo, A.: Fintech and SMEs sustainable business models: Reflections and considerations for a circular economy. J. Clean. Prod. **281**, 125217 (2021)
26. Pyakurel, P., Wright, L.: Energy and resources cooperation for greenhouse gases emissions reduction of industrial sector. Energy & Environment **32**(4), 635–647 (2021)
27. Cappelletti, F., Rossi, M., Germani, M.: How de-manufacturing supports circular economy linking design and EoL-a literature review. J. Manuf. Syst. **63**, 118–133 (2022)
28. Chari, A., et al.: Dynamic capabilities for circular manufacturing supply chains—Exploring the role of Industry 4.0 and resilience. Business Strategy and the Environment (2022)

# Simulation in Additive Manufacturing and Its Implications for Sustainable Manufacturing in the Era of Industry 4.0

Amal Charles[1](✉), Mohamad Bayat[2], Ahmed Elkaseer[1], and Steffen Scholz[1,3,4]

[1] Institute for Automation and Applied Informatics (IAI), Karlsruhe Institute of Technology (KIT), 76344 Eggenstein-Leopoldshafen, Germany
amal.charles@kit.edu

[2] Department of Mechanical Engineering, Technical University of Denmark, Building 425, Lyngby, Denmark

[3] School of Mechanical Engineering (SMEC), Vellore Institute of Technology (VIT), Tamil Nadu, Vellore 632014, India

[4] Karlsruhe Nano Micro Facility, Hermann-Von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

**Abstract.** Additive Manufacturing (AM) technologies, also known as 3D Printing technologies are one of the main driving technologies of the fourth industrial revolution. The main benefits they offer to academic as well as industrial adopters include, increased design complexity freedom, decreased lead times and enhanced functionalities. Additionally, due to AM processes not needing any tooling or material removal, they are also considered to be material and resource efficient. However, there exists a gap in process knowledge and know-how when compared to traditional manufacturing or machining processes which hinders the full deployment of AM technologies. There is especially a gap on understanding the impact of AM on sustainable manufacturing. This paper makes a case as to why further research and development using simulation technologies could enable the filling of this gap. This manuscript presents the benefits that can be gained using simulation of AM processes and the pathways that current research efforts are taking in this regard.

**Keywords:** Additive manufacturing · Sustainable manufacturing · Simulation

## 1 Introduction

Additive Manufacturing (AM) technologies are part of a group of advanced manufacturing technologies that are currently creating a revolution in global manufacturing chains. This has been motivated by their inane ability to offer large design freedoms to engineers that makes more complex components possible. These complex designs can further be enriched by the advanced functionalities and enhanced performances offered by the integration of features such as conformal cooling channels, inclined thin walls


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 370–377, 2023.
https://doi.org/10.1007/978-981-19-9205-6_36

and weight optimization. AM also offers the ability for material optimization through producing lightweight components designed through methods of generative design such as topology optimization. These as well as other additional benefits such as supply chain optimization and new business models enabled by AM have led to their adoption for a wide range of applications in aerospace, automotive, medical and other industries. The applications and implementation of AM in industry and society grows every day.

AM processes are characterized by their method of layer by layer manufacturing. While AM processes themselves can be separated into seven different classes based on their feedstock type and energy source, the basic principle that all of them follow is the layer-by-layer addition of material. Compared to conventional manufacturing/machining processes that are based around the removal of material from a larger block of metal or polymer to achieve the final desired shape, AM does quite the opposite. The process chain for AM begins with the creation of a digital CAD model of the desired part. The CAD file is then converted into a special format for AM through tessellation that depicts the surfaces and planes as triangles called an STL file, or nowadays the CAD file directly is used to build the final print file. The print file which is machine readable by most AM systems is then sliced into numerous layers depending on the desired layer thickness. After which the file is transferred to the AM system for printing. Normally as-built parts from AM systems require some amount of heat treatment or post processing before the components can reach their final desired functionality or design.

AM processes due to their ability for material, design, process chain and weight optimization are considered to be relatively sustainable and several studies have suggested this well. Moreover, several studies also discussed opportunities provided by AM to various industries to streamline supply chains and innovate new business models. Though the real impact of AM on the aspects of sustainability and lifecycle is currently a popular topic that needs a lot more progress to be made in order to be fully understood.

Simulation of manufacturing processes through the usage of simulation software and building process models that replicate the multi-physical and multi-scale behaviour of AM process is an important and popular area of current day manufacturing research. Largely because simulations once validated, provide a trustworthy way to visualize outcomes of various processing conditions without the need for expensive experimental printing. For AM processes true process models have only been developed in the recent past and several avenues to tune and develop these models still continue to exist. However, the connection between simulation of AM and the benefits that may be achieved as a result of this simulation in terms on sustainability is a very unexplored topic. Therefore, this paper will put forward a number of such avenues and the potential benefits on sustainability that each theme can provide. In the upcoming sections, this paper will introduce and discuss the topics of Digital Twins, Modelling and Simulation, Design optimization and Flexible Manufacturing with conclusions and outlooks presented at the end of the paper.

## 1.1 Modelling and Simulation

Numerical modelling of metal AM processes has recently attracted a lot of attention from both academia and industry, since these models, once they are calibrated and validated versus experimental findings, could replace the conventional and laborious trial-and-error and merely-experimental approaches [1]. These numerical simulations, as also noted by many recent review papers in the field, cover a wide range in terms of physics, application, complexity, etc. [2–5]. Therefore, these models could be selected as a smart as well as a reliable tool for predicting a specific quality aspect of metal AM-manufactured parts. This quality aspect ranges from microstructural analyses, where one studies the grain size and orientation and its morphology [6, 7] to melt pool simulations and finally part-scale simulations that are potentially used for understanding the impact of process parameters on the meso- and macro-scale defects such as porosities and deflections, respectively [8–11].

In this respect, instead of going through an expensive experiments-only approach that asks for a comprehensive design-of-experiment, which as underlined earlier is neither cost- nor energy-effective, one could select an alternative path and do a combined numerical-experimental study with limited and at the same time, dedicated experiments. This alternative hybrid approach would, as expected, reduce the material waste to a large extent when compared to the earlier-mentioned experimental approach. Therefore, it is clearly implied that not only does numerical modelling promote and address sustainability in metal AM processes, but also it serves as a tool that can be used for uncovering the mechanisms of defect formation – which is almost impossible to do via ex-situ experimental testing. As an example, Charles et al. used a multi-physics simulation to understand the mechanism behind the formation of a well-encountered surface defect, namely the dross defect, and this model was then used to study how changing of main input process parameters affects the quality of the overhang structures in L-PBF parts [12]. Therefore, in this case, the validated numerical simulation was used as a tool to develop a process window without any need for new experimental samples, and this would to a large degree be beneficial when addressing sustainability. Similar studies, where multi-physics models were used to understand how the input process parameters affect the formation of porosity or the final track shape/quality in metal AM processes [8, 13], show in essence, how one could benefit from numerical simulations to understand the mechanisms of defect formation while keeping the possible material waste at a reasonably low level, compared to conventional experimental approaches. It is interesting to furthermore underline the fact that even earlier studies already showed the potential of using simple models for developing a process map for metal AM processes [9] that could replace unnecessary experimental sample manufacturing.

### 1.2 Digital Twins

Digital Twins (DT) in their most basic form can be defined as a digital representation of a physical object, where the object can be one singular product, or even whole production systems and services. In essence a Digital Twin is theoretically able to accurately act as a replica of a physical object, and therefore should accurately behave as a physical object would [14]. Therefore, it opens up a wide range of applications in the cyber sphere to visualise and predict issues within a process chain in real time. Thereby making it possible to take real time decisions based on predicted key performance indicators. The developments of digital twins is a hot topic, especially for manufacturing processes [15, 16]. However, the creation of digital twins for AM processes is still in early stages of developments, since as mentioned in the previous section, development of process models for AM processes are only currently underway.

The creation of digital twins for AM comes with its own issues. For instance, in metal AM processes, the computational power needed for accurately simulating heat and mass transfer, the melt-pool evolution and solidification rates, internal stress concentrations, the physical distortion of components due to warping etc. is very high. Therefore, real-time analysis and decision making is further complicated by this factor. Furthermore, the exact effects of AM processes, and AM based process chains on sustainability are still in their early stages of investigation. Therefore, there is large progress still to be made in this regard. However, this has not discouraged many researchers to attempt to build first stage digital twins of AM processes. Zhang et al. have presented a literature review of DT for AM processes where they conclude that one of the areas where further research is needed for achieving DT's is in further integrating Artificial Intelligence/Machine Learning techniques that will be the only way to analyse real time data [17]. Knapp et al. developed a three dimensional transient process model that can calculate temperatures, velocity fields, cooling rates, solidification rates and part geometry that can be the key building blocks for a computationally efficient first generation digital twin [18]. Gunasegaram et al. make a strong case for the creation of digital twins of AM processes, where they say that businesses can also benefit from DTs as increased confidence can be gained in process reliability which will increase the scope of AM processes [19]. While product integrity can also be improved which can also significantly reduce testing requirements. Furthermore, DTs can help assure a quality process which can help reduce defected components. Additionally, with increased first-time-right production, plant productivity will only be increased. On a more holistic level, Scime et al. have created a scalable digital platform based on a cyberphysical infrastructure that will help build the digital twins where they say that the entire AM product lifecycle needs to be integrated into the digital model to make DTs realisable [20]. Mandolla et al. proposed the usage of blockchain technology, which offers traceability applications, exploiting which industry specific DTs for AM processes can be built [21]. Guo et al. have also proposed a similar framework for personalised production based on blockchain [22]. Bartsch et al. also reiterate what others have said, which is that the role of AI is vital for creation of DTs for AM [23].

It becomes quite clear that though the current state of the art is still distant from realising DTs of AM processes, the benefits that can be incurred make it a valid pursuit. While the benefits mentioned may mostly be process based, the incurred sustainability benefits can also be justified. Firstly, with the predictive capacities of DTs, reduced testing requirements make it possible to save energy and resources that will otherwise be exhausted. Secondly, improved first-time-right products and decreased defects means that materials are not wasted. This helps to increase the overall material efficiency and therefore results in improved sustainability. A vision for such a Digital Twin enabled AM factory is presented in Fig. 1.

### 1.3 Design Optimization

The design freedom offered by AM processes is one of the major benefits associated with its implementation. AM gives designers the ability to design components using

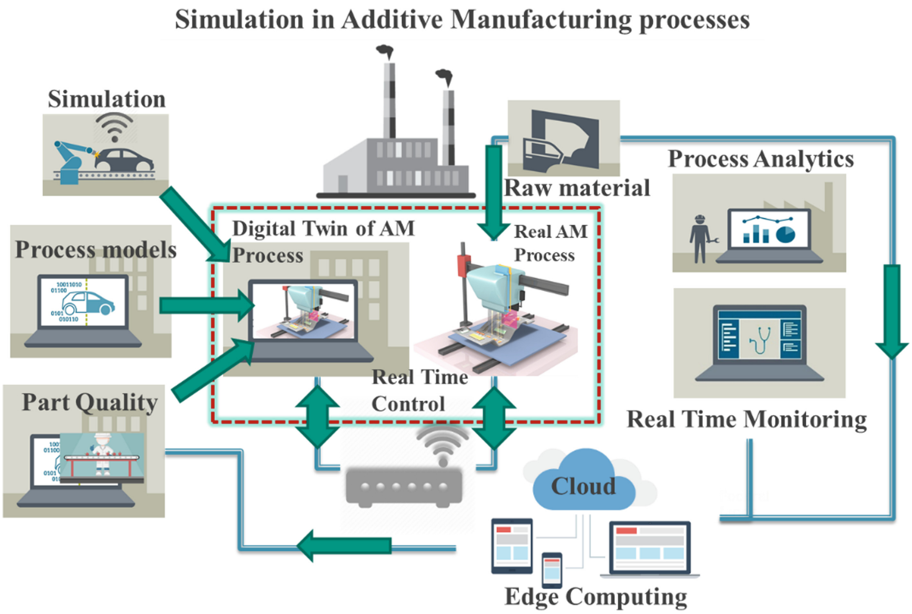



**Fig. 1.** A vision for digital twin enabled additive manufacturing

techniques such as topology optimization where parts can be designed in 3D in such as way such that the designs can be made that fulfill the required functionality while also only containing materials where it is needed. This has created new opportunities for components with improved properties and improved weight optimization. Most of the time, topologically optimized designs possess challenging features that are only realizable by taking advantage of AM's capabilities. Therefore the integrated research of implementing topology optimization with additive manufacturing is a popular theme. The further connection to sustainability is however not a much explored topic with only preliminary investigations being reported. Martens et al. in an attempt to optimize concrete structures in the design phase itself, created a topology optimization method which included material and manufacturing constraints [24]. Their developed topology optimization method created optimized concrete structures with improved feasibility and sustainability. Another approach is shown by the works of Kalliorinne et al. who utilized topology optimization for the optimization of hydrodynamic thrust bearings' designs such that they have lower friction and higher load carrying capacity, thereby increasing the efficiency and thereby the sustainability of the processes that they are a part of [25]. Tsavdaridis et al. showed that through structural topology optimization, aluminium cross sectional designs can be generated that are lightweight, corrosion resistant and also display an improved weight-to-stiffness ratio while still saving the amount of material needed to print it [26].

### 1.4 Flexible Modular Manufacturing

The recent transformation of manufacturing systems into flexible and modular systems due to the need for fulfilling varying customer demands process monitoring, modelling and simulation become more and more significant. Those manufacturers with access to better simulators and predictors of the manufacturing processes have an edge over their competitors, with an increased process efficiency for both economic efficiency and quality of the product [27].

Following the first micro revolution initiated by the raise of Silicon MEMS, smart multimaterial microsystems are now gaining importance as critical enabling components of a variety of macro products in many application areas in both traditional and emerging market sectors [28].

While there are few examples of truly high-volume 3D flexible manufacturing, there is a growing demand for fabrication facilities that can cope with variable volumes and be cost effective for small batch sizes as well as high volume manufacture [29]. Today's fabrication methods requires complex and expensive tooling where the cost to benefit ratio of incorporating functionality is too risky for the typical laboratory, diagnostic or medical device developer. Especially, currently, most of the applications in the flexible and modular manufacturing area are addressing small and medium batch size manufacturing. This is in addition to the high cost for the production facilities for medium volume manufacturing which effectively hinders small companies in bringing new products to the market (production costs are too high to allow for reimbursement). Therefore, a new generation of fabrication methods and manufacturing systems, namely additive manufacturing technologies, is required to address the industrial needs for highly productive, reliable, innovative and efficient processes in 3D micro manufacturing. In order to facilitate this growth however, simulation technologies become vital, especially for SME's since the cost to entry of AM technologies is generally high. Furthermore, simulation and digital twins of AM processes allow the testing of flexible manufacturing systems and to investigate the possibility for scaling up of production.

## 2 Conclusions and Outlook

This paper has presented briefly a case for the usage of simulation technologies in connection with additive manufacturing technologies within the context of improving the sustainability of the overall manufacturing of components. Especially since global trends see major pushes for improved sustainability from the manufacturing industry. This paper summarizes the benefits of simulation for sustainability in the following aspects:

1. Numerical modelling of AM processes can replace costly equipment and material usage. Thereby improving material usage and reducing material wastage.
2. For research, simulations stand to replace costly design-of-experiment studies that are neither cost nor energy efficient.
3. Digital Twins help developed improved confidence on AM processes and can also predict process behavior and final part quality which prevents further energy and material wastage.

4. Digital Twins also reduce testing requirements and create the possibility for more first-time-right products with decreased defects, with overall increased material and equipment usage efficiency.
5. Topology Optimization has shown promise for improved sustainability where parts can be designed in such a way that the fulfill their functionality while reducing material usage.
6. Simulation of production process chains is necessary for circumventing the high costs and resource usage that comes with establishing production facilities, especially ones focused on additive manufacturing. Since initial investment costs with AM are high.

As a digital manufacturing technology, AM stands at the forefront of enabling the next industrial revolution. However there is still a gap in process maturity and confidence that exists when comparing AM processes to conventional manufacturing or machining processes. Simulation is one of the tools that will help bridge this gap. Combining this with other new technologies such as AI will help develop the journey towards sustainable manufacturing even more.

**Acknowledgements.** This work was carried out with the support of the Karlsruhe Nano Micro Facility (KNMFi, www.knmf.kit.edu), a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu) and under the Helmholtz Research Programme STN (Science and Technology of Nanosystems) at KIT.

## References

1. DebRoy, T., et al.: Scientific, technological and economic issues in metal printing and their solutions. Nat. Mater. **18**(10), 1026–1032 (2019)
2. Bayat, M., Dong, W., Thorborg, J., To, A.C., Hattel, J.H.: A review of multi-scale and multi-physics simulations of metal additive manufacturing processes with focus on modeling strategies. Addit. Manuf. **47**, 102278 (2021)
3. Cook, P.S., Murphy, A.B.: Simulation of melt pool behaviour during additive manufacturing: underlying physics and progress. Addit. Manuf. **31**, 100909 (2020)
4. Markl, M., Korner, C.: Multiscale modeling of powder bed-based additive manufacturing. Ann. Rev. Mater. Res. **46**(1), 93–123 (2016)
5. Meier, C., Penny, R.W., Zou, Y., Gibbs, J.S., Hart, A.J.: Thermophysical phenomena in metal additive manufacturing by selective laser melting: fundamentals modeling, simulation, and experimentation. Ann. Rev. Heat Transf. **20**(1), 241–316 (2017)
6. Plotkowski, A., Kirka, M.M., Babu, S.S.: Verification and validation of a rapid heat transfer calculation methodology for transient melt pool solidification conditions in powder bed metal additive manufacturing. Addit. Manuf. **18**, 256–268 (2017)
7. Zinovieva, O., Zinoviev, A., Ploshikhin, V.: Three-dimensional modeling of the microstructure evolution during metal additive manufacturing. Comput. Mater. Sci. **141**, 207–220 (2018)
8. Bayat, M., et al.: Keyhole-induced porosities in Laser-based Powder Bed Fusion (L-PBF) of Ti6Al4V: high-fidelity modelling and experimental validation. Addit. Manuf. **30**, 100835 (2019)
9. Gouge, M., Denlinger, E., Irwin, J., Li, C., Michaleris, P.: Experimental validation of thermo-mechanical part-scale modeling for laser powder bed fusion processes. Addit. Manuf. **29**, 100771 (2019)

10. Lee, Y.S., Zhang, W.: Modeling of heat transfer, fluid flow and solidification microstructure of nickel-base superalloy fabricated by laser powder bed fusion. Addit. Manuf. **12**, 178–188 (2016)
11. Lu, X., et al.: Residual stress and distortion of rectangular and S-shaped Ti-6Al-4V parts by directed energy deposition: modelling and experimental calibration. Addit. Manuf. **26**, 166–179 (2019)
12. Charles, A., et al.: Elucidation of dross formation in laser powder bed fusion at down-facing surfaces: phenomenon-oriented multiphysics simulation and experimental validation. Addit. Manuf. **50**, 102551 (2022)
13. Bayat, M., et al.: On the role of the powder stream on the heat and fluid flow conditions during Directed Energy Deposition of maraging steel—multiphysics modeling and experimental validation. Addit. Manuf. **43**, 102021 (2021)
14. DebRoy, T., Zhang, W., Turner, J., Babu, S.S.: Building digital twins of 3D printing machines. Scripta Mater. **135**, 119–124 (2017)
15. Mukherjee, T., Debroy, T.: A digital twin for rapid qualification of 3D printed metallic components. Appl. Mater. Today **14**, 59–65 (2019)
16. Tao, F., Qi, Q.L., Wang, L.H., Nee, A.Y.C.: Digital twins and cyber-physical systems toward smart manufacturing and industry 4.0: correlation and comparison. Engineering **5**(4), 653–661 (2019)
17. Zhang, L., et al.: Digital twins for additive manufacturing: a state-of-the-art review. Appl. Sci. **10**(23), 8350 (2020)
18. Knapp, G.L., et al.: Building blocks for a digital twin of additive manufacturing. AcMat **135**, 390–399 (2017)
19. Gunasegaram, D.R., Murphy, A.B., Matthews, M.J., DebRoy, T.: The case for digital twins in metal additive manufacturing. J. Phys.: Mater. **4**(4), 040401 (2021)
20. Scime, L., Singh, A., Paquit, V.: A scalable digital platform for the use of digital twins in additive manufacturing. Manuf. Lett. **31**, 28–32 (2022)
21. Mandolla, C., Petruzzelli, A.M., Percoco, G., Urbinati, A.: Building a digital twin for additive manufacturing through the exploitation of blockchain: a case analysis of the aircraft industry. Comput. Ind. **109**, 134–152 (2019)
22. Guo, D., et al.: A framework for personalized production based on digital twin, blockchain and additive manufacturing in the context of Industry 4.0. In: IEEE 16th International Conference on Automation Science and Engineering (CASE), pp. 1181–1186 (2020)
23. Bartsch, K., Pettke, A., Hübert, A., Lakämper, J., Lange, F.: On the digital twin application and the role of artificial intelligence in additive manufacturing: a systematic review. J. Phys.: Mater. **4**(3), 032005 (2021)
24. Martens, P., Mathot, M., Bos, F., Coenders, J.: Optimising 3D Printed Concrete Structures Using Topology Optimisation, pp. 301–309. Springer International Publishing, Cham (2018)
25. Kalliorinne, K., Larsson, R., Almqvist, A.: Application of topological optimisation methodology to hydrodynamic thrust bearings. Proc. Instit. Mech. Eng. Part J: J. Eng. Tribol. **235**(8), 1669–1679 (2021)
26. Tsavdaridis, K.D., Efthymiou, E., Adugu, A., Hughes, J.A., Grekavicius, L.: Application of structural topology optimisation in aluminium cross-sectional design. Thin-Walled Struct. **139**, 372–388 (2019)
27. Biedermann, M., Beutler, P., Meboldt, M.: Routing multiple flow channels for additive manufactured parts using iterative cable simulation. Addit. Manuf. **56**, 102891 (2022)
28. Elkaseer, A., Salem, M., Hagenmeyer, V., Scholz, S.: Vision system-based inspection and alignment of laminated polymer films for 3D-Integration of microsystems. IFAC-PapersOnLine **52**(15), 13–18 (2019)
29. Elkaseer, A., et al.: Replication of overmolded orthopedic implants with a functionalized thin layer of biodegradable polymer. Polymers (Basel) **10**(7), 707 (2018)

# Multi-parameter Analysis for High-Precision Inkjet Printing

Ahmed Elkaseer[1,2](✉), Matthias Kuchta[1], Andrew Rees[3], and Steffen G. Scholz[1,2,4]

[1] Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany
ahmed.elkaseer@kit.edu
[2] Karlsruhe Nano Micro Facility (KNMFi), 76344 Eggenstein-Leopoldshafen, Germany
[3] Department of Mechanical Engineering, Swansea University, Swansea SA1 8EN, UK
[4] College of Engineering, Swansea University, Swansea SA2 8PP, UK

**Abstract.** This study provides insights into the effect of different process parameters on the precision of inkjet printing when producing micro scale features. The parameters examined are printing resolution (which controls the droplets center-to-center distances), printing speed as well as printing mode, whether it is unidirectional or bidirectional. The results show that the smallest possible features were achieved with a resolution of 720 dpi. Prints with a higher resolution of 1080 dpi caused the ink to blur and could not be characterized. However, a lower resolution of 360 dpi resulted in larger, but sharper features. The deviation across all measured resolution is below 20%. The findings of this research help identify proper working conditions for cost-efficient high-throughput prints of high precision features in a sustainable manner.

**Keywords:** Inkjet printing · TIFF resolution · Printing speed · Precision of printed features · Printing direction mode

## 1 Introduction

3D printing (also known as additive manufacturing, AM) has become a smart asset and well-integrated into modern manufacturing systems in the context of Industry 4.0 framework [1]. Although more and more research into this topic is being conducted, still there is a distinct lack of investigation on the achievable precision using this manufacturing technique, especially at sub-millimeter scale. In particular, although multiple investigations have attempted to elucidate the effect of several parameters on the overall accuracy of printed samples, the large body of these studies focused on relative large-scale features [2], the effects of only a single parameter [3], or a conventional inkjet process with a limited number of single nozzles [4]. A more thorough understanding of the effect of multiple process parameters on the precision of sub-millimeter scale features would enable a more sustainable printing process.

In addition to the ability of additive manufacturing to produce a wide range of forms and 3D structures, inkjet printing has the huge potential to print highly accurate features


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 378–387, 2023.
https://doi.org/10.1007/978-981-19-9205-6_37

in the range of a few micrometers [5, 6]. When comparing inkjet printing to other additive manufacturing technologies, such as fused filament fabrication, inkjet printing has been utilized to produce smaller features with high accuracy [7].

2D/3D inkjet printing is highly dependent on jetted ink droplets and their in-flight formation and their physical, mechanical and chemical interaction with other droplets and the substrate [8]. This study aims to experimentally investigate the effect of a number of process parameters on the precision and accuracy of printed features at the micrometer scale. This can be obtained by looking at different parameters that influence the printing process and comparing the outcomes at different levels as well as by comparing the final part with the theoretical TIFF images utilized for printing. To achieve this the experimental work as well as the characterization process is established. This leads to the discussion of the results. Finally, a conclusion is deducted from the discussed results, together with a brief outlook into possible future work in this topic.

## 2 Methodology and Experimental Work

This study examines the effect of three process parameters on the precision and accuracy of printed features. A full factorial Design of Experiment was chosen, due to the fact that the number of examined parameters are fairly low. Those parameters in particular are resolution of the TIFF images, also called printing resolution, printing speed and bidirectional printing mode versus unidirectional print.

### 2.1 Printing Conditions

For the resolution and the printing speed, three different values are chosen. Bidirectional printing on the other hand, can only be enabled, where the droplets will be fired in both directional movement of the printhead or disabled and thus the droplets will be fired in a unidirectional mode. This leads to an overall number of 18 printing trials, as seen in Table 1. The output parameter is the relative deviation of the measured features, to the theoretical value given by the TIFF-image.

The relative deviation percentage (d%) of the printed features is calculated using Eq. 1 as follows.

$$d\% = \text{abs}\left((\text{measured length} - \text{theoretical length})/\text{theoretical length}\right) * 100 \quad (1)$$

**Table 1.** Input factors

| Factor | Unit | Level | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Resolution | dpi | 360 | 720 | 1080 |
| Printing speed | mm/s | 300 | 200 | 100 |
| Bidirectional printing | -- | on | off | -- |

The printing resolution describes the number of pixels in an inch of the TIFF-Image used to print. A higher resolution thus means more pixels per inch and this affects the droplet center-to-center distance, when droplet size remains constant. In this study the resolution levels varied between 360 and 1080 dots per inch (dpi).

The printing speed corresponds to the velocity of the printhead while it is jetting ink on the substrate, and in this study, it is varied between 300 and 100 mm/s.

As previously stated, while unidirectional printing mode lets the printhead fires droplets while moving in one direction, bidirectional printing allows the printhead to jet droplets on the way forward and backward.

To carry out the printing trials, TIFF-images with a binary color, black and while, structure were created, entailing a rectangle with a length of 80 mm and a width of 45 mm with some features inside, as seen Fig. 1.

Looking at the detailed feature, a checker like pattern is located in the lower right half of the model, and from now on will be referred to as a square feature. This is further split up into four sections of squares with four-by-four pixel, three-by-three, two-by-two and one-by-one pixels. Characterization of this feature is done by investigating the areas cover with ink (and called herein as positive features). Another feature are the three forks located in different positions: Two parallel bars with the same width and the same length converging into smaller and smaller bars, with each section having the length of five millimeter. It goes from nine pixels, to six pixels, then to four pixels and down to one pixel at the end. The model overall contains three of these forks, a horizontal, a vertical and a slanted one, to capture any discrepancies in printing directions. These features are characterized by examining the empty space between printed features (termed here as negative features) and can be seen in Fig. 1 below.

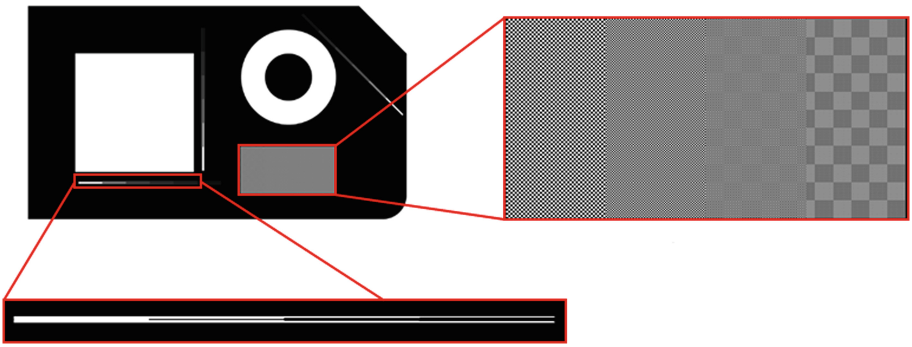


**Fig. 1.** TIFF-Image used for printing

## 2.2 Printing Setup

The machine used for printing is an "n.jet high laydown 3D inkjet" printer by Notion Systems, see Fig. 2. The printhead used in this system is a Konica Minolta "KM1024i" printhead with 1024 nozzles. It prints by using the so called "job" file in combination with Images in the Tagged Image File Format (TIFF). While the TIFF-image determines the printed model, the other file is used for setting up parameters and actual execution.

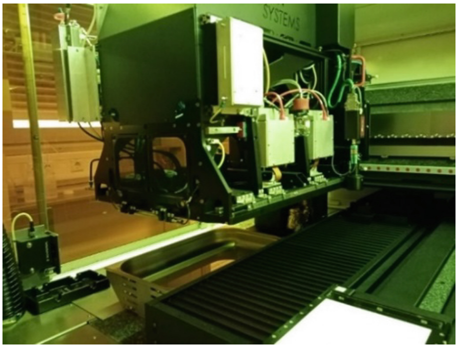



**Fig. 2.** The n.jet high laydown printer by Notion Systems

### 2.3 Printing Trials

To conduct the printing tests, a water based red ink was jetted onto a DIN A4 sheet of glossy photo paper by EPSON. The reason for using a water-based standard ink for the printing trials is to minimize the uncertainty effect that might be introduced due to the complex nature of functional inks. Figure 3 presents an example of the printed samples.

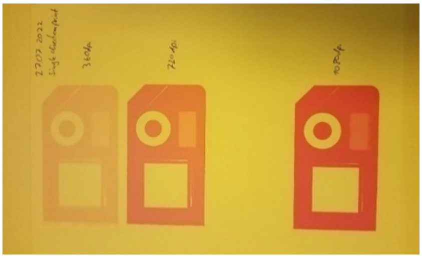


**Fig. 3.** First run of printing samples

### 2.4 Characterization

The printed features were investigated using a ZEISS SteREO Discovery V12 microscope, Fig. 4. A picture was taken of each feature and then measured through its native software. The theoretical scaling provided by the software through examination of the magnification and parts of the microscope was also verified using an appropriate scale. Along the fork shaped features, the width of each bar was measured, as well as the length of each bar. For square features, of each level of pixels, five squares are chosen from the middle and each corner, to account for any abbreviation. The dimensions acquired are all in the micrometer range.

**Fig. 4.** ZEISS SteREO Discovery V12

## 3 Results and Discussion

### 3.1 Results for 360 Dpi Resolution Samples

Figure 5 shows the relative deviation of square features compared to the CAD model for 360 dpi resolution, when printing in a single direction.

For this 360 dpi resolution the length of a pixel would equate to 70.5 µm. Looking at the results reported in Fig. 5 for all printing speed ranges, one can see that as the feature size gets smaller, dimensional deviation increases. Also, it is seen that in this pattern, the slowest speed, 100 mm/s, seems to give the most accurate results, in general. This can be explained by the fact that the lower speed allows for more accurate allocation of the jetted droplets on the substrate, which could not be the case for high printing speed.

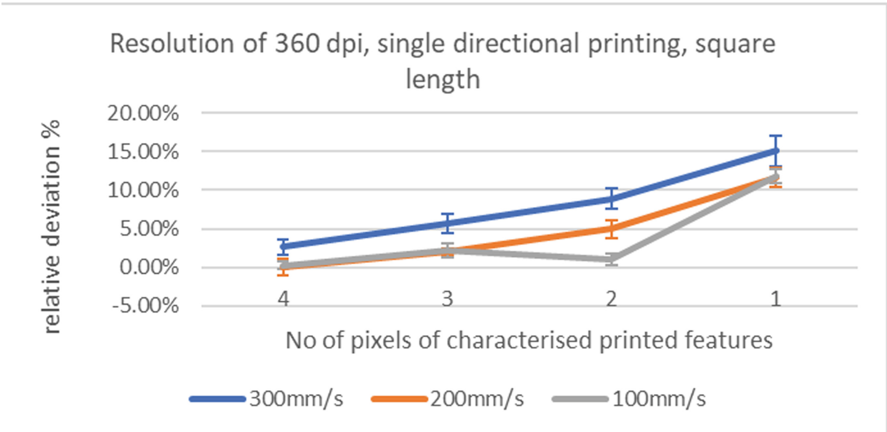



**Fig. 5.** Relative deviation of the square features

When comparing both the bidirectional printing mode with the single directional printed samples as seen in Fig. 6, it is apparent that there is a trend indicating bidirectional printing to decrease relative deviation, especially and more significantly for the one pixel features. Increasing in feature size seems to mitigate these differences between printing modes. This is most apparent when comparing the samples printed at 300 mm/s.

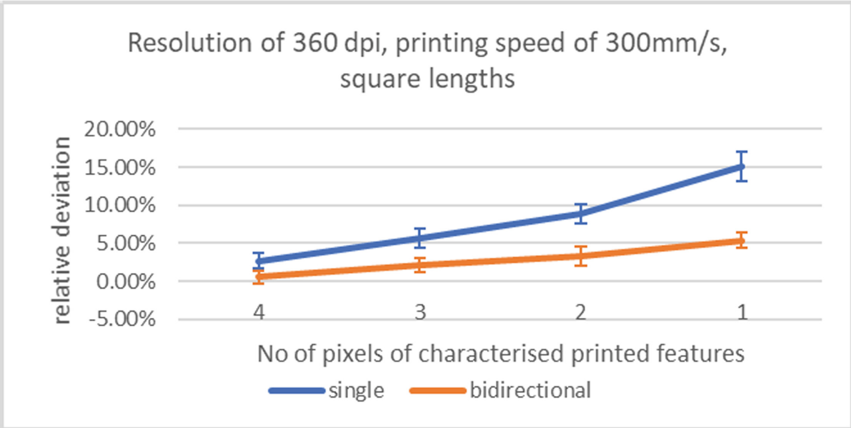



**Fig. 6.** Relative deviation of the squares for single vs bidirectional printing modes

Looking back at the presented results as of so far, it can be concluded that for a resolution of 360 dpi, bidirectional printing is showing better results, as it is shown to produce more accurate features. This is true for both negative features and positive features.

Regarding the accuracies of different printing speeds, especially when looking at square features that utilize single directional printing, 300 mm/s clearly has the higher relative deviation. Overall, the values of percentual deviation were measured to be below 20%. Bidirectional printing of square features seems to give more accurate results for different feature sizes, especially when compared with the single printing speed mode. Adding to this, one can argue that a combination of a bidirectional printing mode and a printing speed of 300 mm/s can give an overall lower deviation, while using 200 mm/s will lead to the highest accuracy of single pixel size features, for this resolution.

### 3.2 Results for 720 Dpi Resolution Samples

The next resolution used is 720 dpi, where the results are illustrated in Fig. 7. Here, the length of a pixel would equate to 35.3 µm, which theoretically leads to a smaller feature size compared to prints were printed using a resolution of 360 dpi.

When taking a look at the results for the square features printed at 720 dpi resolution one can conclude the following: Unlike with the low resolution before, there are a lot of errors in both single and bidirectional samples. As these will be discussed in the next section, only the intact patterns will be discussed here. Beginning with the single directional printed samples, only the two largest square features were printed correctly, leading to the relative deviation across printing speeds illustrated in Fig. 7.

Clearly, the speed of 100 mm/s leads to the largest deviation, while the other printing speeds result in fairly similar deviations. Besides, looking back at the deviation of the

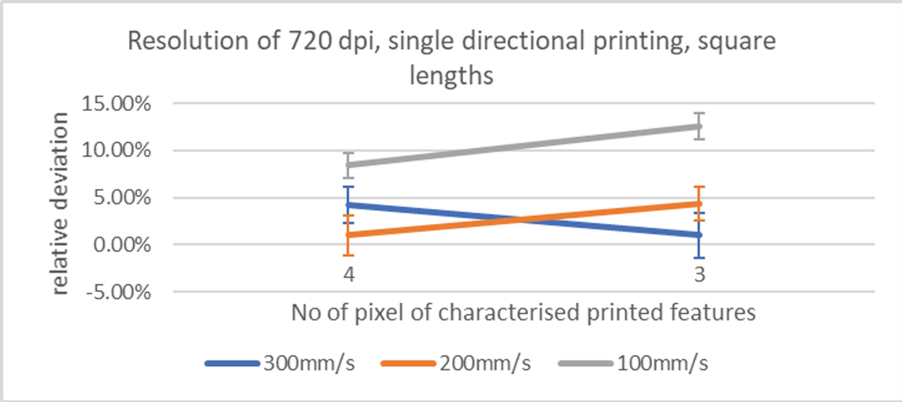



**Fig. 7.** Relative deviation of intact square features using bidirectional printing and a resolution of 720 dpi

lower resolution of 360 dpi, the relative deviations are within the same range. This further confirms that with both resolutions, similar accurate results can be achieved. Nonetheless it should not be neglected that the two-by-two and one-by-one pixel sized square features could not be characterized. Thus, if only similar features need to be printed, that do not go smaller than 70.6 μm, the resolution of 360 dpi should be considered. As for the square features of the bidirectional printing, only the four-by-four pixels sized pattern, while using the speed of 300 mm/s were printed correctly. Here the average relative deviation is 6.57%, making it worse, than the deviation of the samples printed using a single directional printing mode, while not improving the print in any other capacity.

As clearly shown in Fig. 8, the higher resolution leads to a higher spread of ink in the printed samples, while prints using the resolution of 360 dpi, an issue of ink not fully covering the substrate is detected. This higher spread of ink, present in print using higher resolutions also causes the features to show a blur around the edges that caused some features to be unmeasurable, as mentioned before.

In comparison, the resolution of 360 dpi, while not capable of features as small as the higher resolution, allows for sharper edges, while sacrificing full ink coverage. It should also be noted, that prints using higher resolutions took longer to produce, meaning, bidirectional printing could be a way to reduce print time and thus increase output.

### 3.3 Errors in Prints

This section focusses on displaying and showing the errors of the printed samples. The undoubtedly most influencing factor is the resolution of 1080 dpi. Looking deeply at the results, one can see that the small-scale features were not printed correctly, with the square features not being present at all and the fork features smearing into itself. The most likely cause of this is, as seen before, a lower center-to-center distance between droplets, leading to an excess of ink that causes blurring to such a degree, where characterization was impractical.

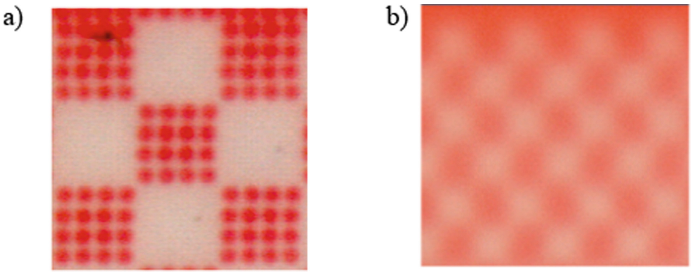



**Fig. 8.** A comparison of square features printed with a resolution of a) 360 dpi, and b) 720 dpi

Figure 9 displays the square features, utilizing two-by-two and one-by-one pixel sized squares, printed with a resolution of 720 dpi. It becomes clear, the two-by-two square feature displays a form of zigzag pattern, instead of uniform squares. Moreover, looking at the one-by-one square feature, no pattern at all is visible. The latter one most likely stems from the blurring of ink already discussed. The first one on the other hand, while seeming to stem from the printing direction at first, appears on all samples using a resolution higher than 360 dpi, as well as in both single and bidirectional printing.

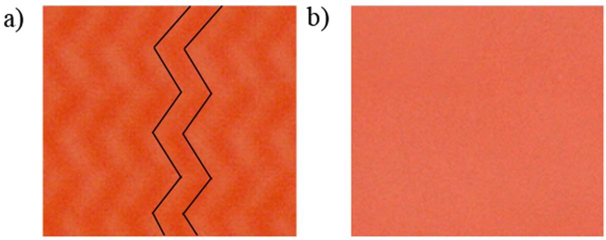



**Fig. 9.** A comparison of square features printed with a resolution of 720 dpi having a pixel size of a) two, and b) one

Another major error in the printed features was found in all trials printed with the resolution of 360 dpi in combination with the bidirectional printing mode. As demonstrated in Fig. 10, the printed feature that is supposed to be straight, shifted. Singling out the TIFF-image used for printing, due to it being the same across all trials printed with a resolution of 360 dpi, it is assumed, and that this causes the problem is the specific combination of the low resolution and the bidirectional printing mode.

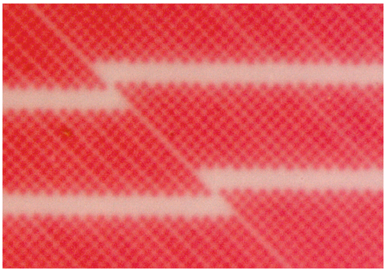


**Fig. 10.** Shifting of printed sample

## 4 Conclusion

This study reported the results of an experimental examination into the precision and accuracy of Inkjet printing in the micrometer scale, comparing the different parameters printing speed, resolution and bidirectional vs unidirectional printing modes.

Looking back at the results, the following can be concluded.

Out of the measurable resolutions investigated in this paper, fairly high accuracy in the micrometer range can be achieved. Both resolutions resulted in a quite similar relative deviation of feature size up to around 20%. The resolution of 720 dpi resulted in smaller features, while also resulting in more uniform printed layers. However, a blur around the edges of printed features becomes noticeable at this resolution.

Due to this blurring effect, it appears that lower resolutions are more favourable for printing positive features. Furthermore, one can conclude that the effect that different printing speeds have on the dimensional relative deviation is minor.

All in all, the results show that inkjet printing can be used for producing accurate small-scale features, and display different effects of the printing parameters. This allows for a more predictable and controllable printing process, while ensuring sustainability at the same time. Nevertheless, the utmost theoretical accuracies are not yet reached, it is very close to doing so. Undoubtedly future work on the field of 2D/3D inkjet printing will advance the possibility and usability of this promising manufacturing method. This future work could include, but is not limited to: Investigating the shifting of printed features that occurred when printing with a resolution of 360 dpi in combination with bidirectional mode. As well as further optimizing printing micro-scale features in higher resolutions to achieve even smaller printed features.

Beyond this, a similar investigation for the 3D dimensional printing, using functional inks could elevate the precision and accuracy achievable for successful implementations of 3D printing.

**Acknowledgement.** This work was carried out with the support of the Karlsruhe Nano Micro Facility (KNMFi, www.knmf.kit.edu) a Helmholtz Research Infrastructure at Karlsruhe Institute of Technology (KIT, www.kit.edu) and under the Helmholtz Research Programme MSE (Materials Systems Engineering) at KIT.

## References


1. Moshiri, M., Charles, A., Elkaseer, A., Scholz, S., Mohanty, S., Tosello, G.: An industry 4.0 framework for tooling production using metal additive manufacturing-based first-time-right smart manufacturing system. Procedia CIRP **93**, 32–37 (2020). https://doi.org/10.1016/j.procir.2020.04.151
2. Charles, A., Bayat, M., Elkaseer, A., Thijs, L., Hattel, J.H., Scholz, S.: Elucidation of dross formation in laser powder bed fusion at down-facing surfaces: phenomenon-oriented multiphysics simulation and experimental validation. Addit. Manuf. **50**, 102551 (2022)
3. Zhao, P., et al.: Modelling the influence of UV curing strategies for optimisation of inkjet based 3D printing. Materials & Design **208**, 109889 (2021). ISSN 0264-1275. https://doi.org/10.1016/j.matdes.2021.109889.
4. Willert, A., Tabary, F.Z., Zubkova, T., Santangelo, P.E., Romagnoli, M., Baumann, R.R.: Multilayer additive manufacturing of catalyst-coated membranes for polymer electrolyte membrane fuel cells by inkjet printing. International Journal of Hydrogen Energy **47**(48), 20973–20986 (2022). ISSN 0360–3199. https://doi.org/10.1016/j.ijhydene.2022.04.197
5. Derby, B.: Inkjet printing of functional and structural materials: fluid property requirements, feature stability, and resolution. Annu. Rev. Mater. Res. **40**, 395–414 (2010). https://doi.org/10.1146/annurev-matsci-070909-104502
6. Elkaseer, A., Schneider, S., Deng, Y., Scholz, S.G.: Effect of process parameters on the performance of drop-on-demand 3D inkjet printing: geometrical-based modeling and experimental validation. Polymers **14**, 2557 (2022). https://doi.org/10.3390/polym14132557
7. Blynskaya, E.V., Tishkov, S.V., Alekseev, K.V., Vetcher, A.A., Marakhova, A.I., Rejepov, D.T.: Polymers in technologies of additive and inkjet printing of dosage formulations. Polymers **14**, 2543 (2022). https://doi.org/10.3390/polym14132543
8. Magazine, R., van Bochove, B., Borandeh, S., Seppälä, J.: 3D inkjet-printing of photo-crosslinkable resins for microlens fabrication. Addit. Manuf. **50**, 102534 (2022). https://doi.org/10.1016/j.addma.2021.102534

# Identifying Platform Candidates in the Process Industry: A Proposal for a Practitioner-Oriented Method

Rasmus Andersen[1](✉), Francesco Gabriele Galizia[2], and Marco Bortolini[2]

[1] Department of Materials and Production, Aalborg University, Aalborg, Denmark
rasmus@mp.aau.dk
[2] Department of Industrial Engineering, University of Bologna, Bologna, Italy
{francesco.galizia3,marco.bortolini3}@unibo.it

**Abstract.** Manufacturing companies are increasingly pressured by various market changes across both discrete manufacturing and process manufacturing industries. This has forced manufacturers to adopt more efficient product development approaches to deliver the required product variety in a cost-efficient manner. In discrete manufacturing industry, platform-based methods have been successfully applied at scale to solve this issue while the process industry is lacking behind. With outset in the unique characteristics of process industry products, platform development methods from discrete manufacturing industry are reviewed and it is found that none of these sufficiently accommodate the needs of process industry products such as accounting for production sequence constraints or the inability to disassemble process industry products. To accommodate these needs, a method for identifying product platform candidates in the process industry is proposed including a novel algorithm to assist in this endeavor. The method is comprised of two phases and seven comprising steps from initial delimitation of product families to the final review and selection of feasible product platform candidates. The method allows practitioners to first identify the most relevant product family to implement product platforms and identifies potentially relevant product platform candidates, enabling process industry manufacturers to adopt platform-based product development approaches.

**Keywords:** Product platform · Process industry · Complexity management · Decision support · Product development

## 1 Introduction

Some decades ago, markets were characterized by consumers having few product varieties to choose from and manufacturers could optimize product development and production to focus exclusively on economies of scale – high output at low costs. However, since the 1980s markets have shifted [1] requiring manufacturing companies to deliver new product variants faster, cheaper, in smaller batches, and to the specific needs of customers. For companies relying on traditional product development and production


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 388–397, 2023.
https://doi.org/10.1007/978-981-19-9205-6_38

approaches, such external pressure strains their ability to accommodate these needs cost effectively [2], which in consequence negatively impacts their competitiveness. That is, unless the manufacturers change their product and production development approaches to fit these changed market needs. Several companies have successfully adopted the principles of platform-based products to exploit both economies of scale and economies of scope simultaneously. Multiple industry examples of successful application of this development approach can be found in literature [3]. However, most of these examples are of products from the discrete manufacturing industry (e.g., cars and consumer electronics), with literature and industry examples of products from the process manufacturing industry (e.g., food, beverages, and chemicals) being much scarcer [4]. This is despite the process industry accounting for more than 50% of the total turnover generated by manufacturing companies in the European Union in 2018 [5]. Andersen et al. [4] found that the unique characteristics of process industry products may make the adoption of platform-based product development techniques more difficult. Recognizing this research gap, the objective of this paper is, therefore, to present a practitioner-oriented method for the identification of product platform candidates.

### 1.1 Process Industry Characteristics and Potential Impact on Platform-Based Products

Manufacturing industry can basically be divided into two: discrete manufacturing industry and process manufacturing industry [6]. The distinction between these two types of industries can be based on different perspectives, such as the product characteristics [7] or process characteristics [8], which may impact the applicability of platform-based approaches for product development [4].

Whereas products from discrete manufacturing industry are produced through assembly operations, where modules or components are combined by means of different fastening techniques (e.g., screwing, bolting, or welding), products from the process industry are typically produced by combining different materials or ingredients by means of e.g., mixing or blending operations [6]. The consequence of these fundamentally different approaches to product "assembly" leads to another defining characteristic of process industry products: a homogeneous appearance. While the composition and structure of most discrete industry products can be deduced from disassembling the product and inspecting its comprising components, process industry products are uniform in appearance [9]. Furthermore, most process industry products cannot be disassembled, as mixing operations or chemical reactions result in homogenized structures or identifiably different materials [10]. The presence of chemical reactions or other transformative processes typically means that the production of process industry products is very sequence dependent. Several more differentiating characteristics can be found in literature, and the reader is referred to Abdulmalek et al. [8] and Lyons et al. [7] for extensive insights into the differences between discrete and process industries.

Based on these findings, the objective of this study is, therefore, to present a proposed approach to identify feasible platform candidates for production sequence-constrained products in a process industry context. To achieve this, Sect. 2 reviews related literature on product platform design methods in relation to process industry characteristics. Section 3, then, introduces the proposed method to identify platform candidates. Lastly, Sects. 4 and 5 discuss and conclude the study, respectively.

## 2 Related Literature

Despite the unique characteristics of process industry products, in comparison to discrete industry products, Andersen et al. [4] identified instances of process industry products developed through methods originating from the discrete industry. Based on these findings, they suggested a possibility for adopting existing methods from the discrete industry to the context of the process industry. For this reason, we performed a review of the literature on platform-based product development methods from the discrete industry. This section presents the findings from the included papers, which were reviewed in relation to their key features.

### 2.1 Product Platform Identification Methods from Discrete Industry

Introducing a flexible platform concept, which facilitates product customization by allowing variable size and shape, Dahmus et al. [11] utilizes function structures, which relies on a combination of expert inputs, physical principles, and interactions between components to identify platform candidates. Li et al. [12] likewise proposes a concept for a flexible platform, which is designed based on a combination of design structure matrix and clustering techniques. Combining sensitivity analysis with clustering techniques, Dai and Scott [13] seeks to solve the issue of scalable multi-platform product family design.

Nayak et al. [14] takes an optimization-based approach to platform design and seeks to minimize product variation required to satisfy the desired product variety in a product family, where desired product variety is expressed by means of performance requirements. Simpson et al. [15] likewise uses optimization techniques in conjunction with performance requirements yet focuses on their application for scalable platform designs. The same applies to De Weck et al. [16] and Willcox and Wakayama [17], who seeks to maximize product family profits and multiple product variants simultaneously, respectively. Focusing specifically on automotive body design, Torstenfelt and Klarbring [18] seeks to optimize product families by means of physical parameters such as shape, size, and topology.

An interesting approach is presented by Hanafy and Elmaraghy [19], who propose the utilization of disassembly tasks as a means of efficiently generating product variants. Extending this principle, Galizia et al. [20] likewise approaches the issue of product platform design and efficient product variant generation by allowing both assembly and disassembly tasks. However, their approach takes inspiration from biology by employing phylogenetic networks and trees to identify feasible platforms.

### 2.2 Implications for Process Industry Application

Most of these methods employ optimization techniques, and some assumes the ability to model product performance as a response of input variables such as product parameters or design variables. Several studies used the DSM in their platform design methodology, and while this tool has been applied widely for modular product design, it only considers product components and not production sequence constraints in the formation of modules. As the production sequence may have significant influence on the complete product, the omission of this parameter in most of the reviewed studies may result in infeasible design concepts. Also related to the production process, some studies exploit disassembly tasks as a means of efficient product variant generation. While this may be feasible for assembled products, where the assembly tasks can be reversed to retrieve components from a product, this is generally not feasible in the process industry, making this approach unsuitable for process industry products. Other studies appear tailored towards specific industries such as aircraft design [17] or automotive design [16]. The nature of these methods makes them challenging to adopt to contexts dissimilar from their original settings.

## 3 Method for Product Platform Candidate Identification

This section introduces the proposed method, as shown in Fig. 1, for identifying platform candidates for production sequence constrained process industry products. Each of the two main parts of the method, i.e., selection of a product family and identification of product platform candidates, are then described.

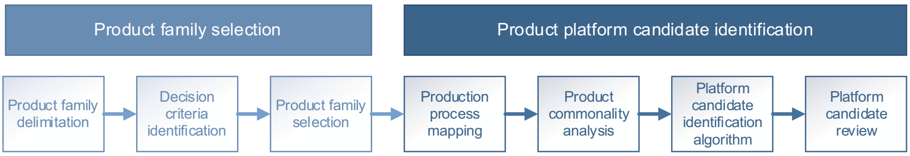



**Fig. 1.** The method for identifying product platform candidates for production sequence-constrained products.

### 3.1 Product Family Selection

Companies typically have multiple product families and identifying the product family with the highest potential gain from implementing platforms can therefore be challenging. To assist in this, the first phase of the proposed method focuses on delimiting the analysis to a single product family based on multiple measures that act as decision support to product developers.

**Initial Product Family Delimitation**

Platforms are recognized for enabling companies to exploit economies of scope and scale for product families with benefits across company functions [3]. Even so, introducing product platforms may also bring drawbacks [21]. The delimitation of product families should, therefore, be based on multiple measures that balances these perspectives. To aid in this delimitation, application of the measures described in Table 1 is proposed.

**Table 1.** Proposed measures for selecting product families which could benefit from implementing product platforms.

| Measure | Description |
|---|---|
| Demand volatility | Coefficient of Variation (CoV) of customer orders for product variants within the product family |
| Annual production volume | Total amount of products produced within the product family on an annual basis |
| Product variety | Number of different product variants currently offered within the product family |
| Projected annual financial value | The revenue of the product family over a specified period multiplied by the average change in revenue over the same period |
| Product life cycle stage | The estimated remaining lifetime of a product family |

The negative effects of volatile demand of individual product variants can be reduced by basing the product family on a platform as the resulting aggregation of demand of the platform will allow for more efficient production of the platform. Thus, product families characterized by high demand volatility may benefit from implementing a product platform. Product families with moderate to high annual production volume and or moderate to high product variety could potentially benefit from a product platform as the resulting economies of scale and scope could provide, among other benefits, lower product costs and faster production lead time [3, 21]. Naturally, product families with a higher financial value would be of interest due to a potentially larger impact on the company. However, the financial value of a product family can be expressed by multiple measures, such as revenue or profit generated by a given product family over some period. Such a measure would, however, only provide a historical perspective without any perspective towards potential changes. For this reason, the compound measure described in Table 1 is used to provide a more nuanced estimate of the financial value. Finally, as development costs for product platforms can be substantial [3], it is relevant to consider the expected remaining lifetime of the product family to ensure that investments can be recouped. To reduce product families which are relatively less relevant from a product platform perspective, only those with scores above the median should be considered for further analysis.

**Identification of Context-Dependent Decision Criteria**

It is recognized that since every company is unique, additional context-specific measures may be relevant, and should be included as additional assessment parameters. Therefore, to assist companies in identifying additional relevant measures, inspiration from related literature may be sought. For example, related to manufacturing postponement strategies, which are typically applied for platform-based products, Olhager [22] proposed a list of 15 different decision criteria, covering market, product, and production aspects. While this list is considered generic, and postponement has been applied in the process industry [23], the unique characteristics of the process industry and the specific context of a company may call for additional criteria. These may be identified through, e.g., interviews with key stakeholders in the company.

**Final Product Family Selection**

Having performed an initial delimitation of the product families, the question becomes which would be most feasible to identify platforms for. Since the evaluation of the product families depend on multiple measures and the number of product families can still be considerable, applying a multi-criteria decision making (MCDM) method would facilitate such a decision process. Although numerous MCDM methods exist [24], a well-recognized method is the Analytic Network Process (ANP), which is a generalized version of the Analytic Hierarchy Process developed by Saaty [25]. Since the issue of selecting a suitable product family is based on multiple criteria which may depend on each other, the ANP is preferable to AHP as it accounts for such dependencies. Once the decision problem for the ANP model has been formulated, the criteria and sub-criteria for the decision problem should be identified. It is proposed that this information is acquired by combined use of literature and expert input from the company. The result is a rank-ordered list of the product families according to their perceived importance across the included measures.

## 3.2 Product Platform Candidate Identification

Having selected the most relevant product family from a platform-based development perspective, the next phase is concerned with identifying such platform candidates. To achieve this requires four different steps focusing on 1) mapping the generic production process, 2) analyzing material commonality across major process steps, 3) identifying potentially feasible platform candidates, and 4) reviewing identified candidates for implementation potential. Each of these steps is elaborated in the following sub-sections.

**Process Mapping**

The consideration of production sequence constraints obviously requires knowledge of the production process and its comprising phases. While some companies may have sufficiently detailed routing and process information available, as in the pharmaceutical industry, for example, other companies may not have this information readily available. In such cases, defining a generic production process sequence could be done by means of interviews with production managers or analyzing shopfloor documents, such as product mixing instructions, which may not lend themselves readily to quantitative analysis. When analyzing the production processes, the division into major phases should be done based on occurrences of break points in the process, such as reactions or material transformations. This is because combining some materials used in reaction with materials to be used after the reaction may be infeasible in practice. The outcome of this phase is a generic representation of the production sequence for the product family investigated and an indication of the major process phases that the products go through.

**Commonality Analysis**

As platforms are about sharing elements, it would seem logical that the greatest potential for identifying platform candidates would be found in production process steps which have the highest degree of commonality among the materials used. Furthermore, the potential presence of reactions limits the ability to define platforms that transcends defined phases, thereby limiting the scope of platform candidate identification to be within individual process phases. Several commonality measures have been proposed in literature [21]. Thevenot and Simpson [26] compared six different commonality metrics and developed a framework to support selection of metrics concerning the specific focus of the analysis, whether that is component cost, number of components, number of common components, or non-differentiating components. The result of this commonality analysis is a list of the identified process phases and their corresponding commonality scores, from which the highest scoring process phase can be selected for further analysis in the following step.

**Longest-Chain Identification Algorithm**

Once a specific process step has been selected, the search for platform candidates can commence. This is done by means of an algorithm, the purpose of which is to identify chains of common materials across product variants within the selected product family and calculate a compound metric, representing the estimated value of a given platform candidate. Before the algorithm can start, the correct data must be supplied to the algorithm. The required data is a collection of all the bill-of-materials for the product variants within the selected product family, corresponding production routings, material cost data, and annual production volume. Next, the first material with complete commonality, among the analyzed bill-of-materials is selected. For each product variant, the algorithm then searches materials which are immediately adjacent in the production routing to the selected material and calculates their commonality, beginning with the preceding material. If this material has the same commonality score, the algorithm logs both materials as comprising a chain of length two. The algorithm then selects the material preceding and repeats this process until a material with lower commonality is reached or no more materials are available within this process step. Then, starting from the original material, the algorithm performs the same calculations in a forward direction using similar terminating conditions. In case additional materials have a commonality score of 1.0, and are not already included in the logged chain, the algorithm repeats the process of searching adjacent materials for this material, logging any chains of two or more materials as a new chain. Each logged chain then represents an identified platform candidate which adheres to process sequence constraints.

If any platform candidates are identified, the next step is then the calculation of their value as represented by the sum of the three parameters, i.e., annual volume consumed, material cost, and length of the chain, which together provides a more nuanced perspective on the potential value of the platform candidate to the company.

**Candidate Review**

Having identified one or more platform candidates and calculated their potential value, the candidates must be reviewed by company experts to ensure practical feasibility. This is important as the method serves as a decision support system rather than providing validated product platform designs. Furthermore, companies may have additional context-specific criteria or evaluation parameters, which are not included in the method but may impact design decisions.

## 4 Discussion

As noted in Sect. 1, the process industry is a large industry comprised of many different sectors. This means that while the preliminary method proposed in this study aims to assist companies in the process industry at large, it is not possible to state how large a share of the process industry this method will apply to without further modification. On the other hand, it can be argued that due to the potential differences among companies in the process industry, developing a completely generic method would be infeasible as such a model would presumably be too rigid to fit individual needs or too complex to be of practical use.

While the proposed method focuses exclusively on platform candidates, defined as chains of adjacent materials with a commonality score of 1.0, product designers may also be interested in what could be referred to as near-platform candidates defined as chains of adjacent materials with commonality scores $< 1,0$, as some of these may prove valuable to leverage into platforms by redesigning some products in the product family.

Lastly, as also briefly noted in Sect. 3.1, the topic of manufacturing postponement and delayed product differentiation are concepts closely related to product platform development. To accommodate companies interested in this aspect, the algorithm could be adjusted to start with the first material in the production sequence and then exclusively search forward to identify potentials for a common base to facilitate manufacturing postponement.

## 5 Conclusions and Further Research

Based on an identified need for a method to support product platform development of production sequence constrained products in the process industry, this study has proposed a preliminary method to accommodate this. Reviewing related literature on platform development methods demonstrated that although numerous studies from discrete industry exist, they are ill-suited for application in the process industry due to the unique characteristics of most products in this industry. Consequentially, a two-phase preliminary method comprising seven individual steps from the initial delimitation of a company's product families to the final review and selection of identified product platform candidates was proposed. An important element of this method is a proposed algorithm that identifies sequence-constrained platform candidates. The proposed method for product platform candidate identification would enable practitioners to identify platform candidates while accommodating context-specific criteria and using only basic product and production information available in most manufacturing companies.

## References

1. Koren, Y.: The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems. John Wiley and Sons (2010)
2. Piya, S., Shamsuzzoha, A., Miftaur Rahman Khan Khadem, M., al Kindi, M.: Supply chain complexity drivers and solution methods. Int. J. Supply Chain Manage. **6**, 43–50 (2017)

3. Simpson, T.W., Siddique, Z., Jiao, J.R.: Platform-based product family development. In: Simpson, T.W., Siddique, Z., Jiao, J.R. (eds.) Product Platform and Product Family Design, pp. 1–15. Springer, New York (2006). https://doi.org/10.1007/0-387-29197-0_1
4. Andersen, R., Brunoe, T.D., Nielsen, K.: Platform-based product development in the process industry: a systematic literature review. International Journal of Production Research, pp. 1–24 (2022). https://doi.org/10.1080/00207543.2022.2044085
5. Eurostat: Manufacturing statistics - NACE Rev. 2, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Manufacturing_statistics_-_NACE_Rev._2#Sectoral_analysis
6. King, P.L., Kroeger, D.R., Foster, J.B., Williams, N., Proctor, W.: Making CEREAL not CARS. Ind. Eng. **40**, 34–37 (2008)
7. Lyons, A.C., Vidamour, K., Jain, R., Sutherland, M.: Developing an understanding of lean thinking in process industries. Production Planning and Control **24**, 475–494 (2013). https://doi.org/10.1080/09537287.2011.633576
8. Abdulmalek, F.A., Rajgopal, J., Needy, K.L.: A classification scheme for the process industry to guide the implementation of lean. Eng. Manag. J. **18**, 15–25 (2006). https://doi.org/10.1080/10429247.2006.11431690
9. Frishammar, J., Lichtenthaler, U., Kurkkio, M.: The front end in non-assembled product development: a multiple case study of mineral- and metal firms. J. Eng. Technol. Manage. - JET-M. **29**, 468–488 (2012). https://doi.org/10.1016/j.jengtecman.2012.07.001
10. Floyd, R.C.: Liquid Lean: Developing Lean Culture in the Process Industries. CRC Press, Boca Raton (2010)
11. Dahmus, J.B., Gonzalez-Zugasti, J.P., Otto, K.N.: Modular product architecture. Design Studies **22**, 409–424 (2001). https://doi.org/10.1016/S0142-694X(01)00004-7
12. Li, Z., Cheng, Z., Feng, Y., Yang, J.: An integrated method for flexible platform modular architecture design. J. Eng. Des. **24**, 25–44 (2013). https://doi.org/10.1080/09544828.2012.668614
13. Dai, Z., Scott, M.J.: Product platform design through sensitivity analysis and cluster analysis. J. Intell. Manuf. **18**, 97–113 (2007). https://doi.org/10.1007/s10845-007-0011-2
14. Nayak, R.U., Chen, W., Simpson, T.W.: A variation-based methodology for product family design. In: Proceedings of DETC 2000, pp. 701–710 (2000)
15. Simpson, T.W., Maier, J.R., Mistree, F.: Product platform design: method and application. Res. Eng. Design **13**(1), 2–22 (2001). https://doi.org/10.1007/s001630100002
16. de Weck, O.L., Suh, E.S., Chang, D.: Product family and platform portfolio optimization. In: Proceedings of the ASME Design Engineering Technical Conference, pp. 175–185 (2003)
17. Willcox, K., Wakayama, S.: Simultaneous optimization of a multiple-aircraft family. J. Aircr. **40**, 616–622 (2003). https://doi.org/10.2514/2.3156
18. Torstenfelt, B., Klarbring, A.: Conceptual optimal design of modular car product families using simultaneous size, shape and topology optimization. Finite Elem. Anal. Des. **43**, 1050–1061 (2007). https://doi.org/10.1016/j.finel.2007.06.005
19. Hanafy, M., Elmaraghy, H.: A modular product multi-platform configuration model. Int. J. Comput. Integr. Manuf. **28**, 999–1014 (2015). https://doi.org/10.1080/0951192X.2014.941407
20. Galizia, F.G., ElMaraghy, H., Bortolini, M., Mora, C.: Product platforms design, selection and customisation in high-variety manufacturing. Int. J. Prod. Res. **58**, 893–911 (2020). https://doi.org/10.1080/00207543.2019.1602745
21. Johnson, M.D., Kirchain, R.E.: Developing and assessing commonality metrics for product families. In: Advances in Product Family and Product Platform Design: Methods and Applications, pp. 473–502. # IEEE (2014)
22. Olhager, J.: Strategic positioning of the order penetration point. Int. J. Prod. Econ. **85**, 319–329 (2003). https://doi.org/10.1016/S0925-5273(03)00119-1

23. Ferreira, K.A., Flávio, L.A., Rodrigues, L.F.: Postponement: bibliometric analysis and systematic review of the literature. Int. J. Logistics Systems and Manage. **30**, 69–94 (2018)
24. Thakkar, J.J.: Multi-Criteria Decision Making. Springer Nature, Singapore (2021). https://doi.org/10.1007/978-981-33-4745-8
25. Saaty, T.L.: Decision making with the analytic hierarchy process. Int. J. Services Sciences. **1**, 83–98 (2008)
26. Thevenot, H., Simpson, T.: Commonality indices for product family design: A detailed comparison (2006). https://www.tandfonline.com/action/journalInformation?journalCode=cjen20

# Embodied Energy Assessment of the Remanufacturing Cleaning Process: A Proposed MRIO-Methodology Framework

Okechukwu Okorie[1(✉)], Jennifer D. Russell[2], and Konstantinos Salonitis[3]

[1] University of Exeter, Exeter, UK
o.s.okorie@exeter.ac.uk
[2] Virginia Polytechnic Institute and State University, Blacksburg, VA 24060, USA
[3] Cranfield University, Cranfield, UK

## 1 Extended Abstract

Fast depleting natural resources, increasing environmental consciousness amongst stakeholders, the development of globalized markets, and the implementation of stringent laws have compelled consumers across the globe to adopt more sustainable production and consumption practices [1]. Thus, manufacturing supply chains processes no longer focus only on the traditional flow of products which characterizes the linear economy. Circular economy approaches, such as remanufacturing contribute to reducing the consumption of resources and generation of waste. In a circular economy, the resources and value are recouped from the end-of-life (EoL) and end-of-use (EoU) products [1, 2]. Recycling, repair, reuse, refurbishing and remanufacturing, are some of the circular economy approaches which are employed at the end of life of the product [3, 4]. Remanufactured mechanical products make up most of the remanufacturing industry, with aeronautical and automotive parts accounting for 67% of the European market [5, 6]. The high added value and their environmental performance continues to make remanufacturing a topic in discussion amongst academia, industry practitioners and government policymakers. Furthermore, remanufacturing has been argued to rank higher than other circular approaches, such as recycling and refurbishment, and is expected to result in gaining much greater energy reduction and materials conservation [7]. Thus many countries have pursued remanufacturing policies and are considering pursuing these policies [8, 9].

Product remanufacturing is an industrial process which is a commonly accepted product reuse strategy in many industries as it has the advantage of ensuring that the remanufactured products have the same quality, functionality and warranty as new products [10]. This complicated systems engineering practice is captured in Fig. 1, adapted from Peng et al. [7]. As compared to recycling, remanufacturing retains a significant portion of economic value added and embodied energy associated with the initial manufacturing stage. It therefore extends the useful life associated with the original product, with associated environmental benefits as well as business benefits for remanufacturers. The remanufacturing process consists of a sequence of operations which includes product recovery, sorting, disassembly, cleaning, inspection, reconditioning, reassembly, final inspection and testing of the remanufacturing product [11, 12]. Cleaning processes in the


S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 398–402, 2023.
https://doi.org/10.1007/978-981-19-9205-6_39

remanufacturing operations may be just one process after the initial sorting of products or may have multiple cleaning stages. For example, Fig. 1 shows multi-stage cleaning processes in between core disassembly [7]. Liu et al. [13] describe a remanufacturing process that includes five distinct cleaning stages within the multistage process, captured in Fig. 2. Generally, the cleaning stage within remanufacturing practices are relatively rough, such as an artificial rinse for the convenience of disassembly and sorting, and do not require much energy or high-technologies [7]. Prior research has identified the cost of cleaning to be quite high, secondary only to the cost of replacement of cores [13]. Thus, for remanufacturers, cleaning is a highly critical aspect of the remanufacturing process [12, 14]. Also embodied energy and environmental effects are rarely considered in practice [15, 16].

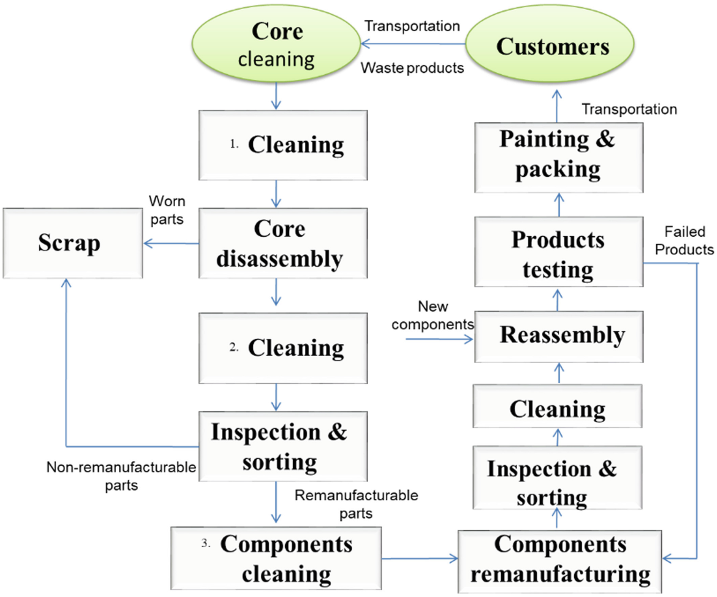



**Fig. 1.** A multistage cleaning remanufacturing flow diagram. Adapted from Peng et al. [7]

Several studies which examine remanufacturing cleaning exist in the literature. These include the study on remanufacturing cleaning technology in mechanical equipment process, which qualitatively reviewed five cleaning technologies [15]. Other studies include Peng et al [7] which investigates whether newly emerged cleaning methods have the environmental superiority and to figure out hotspots for environmental performance promotion using life cycle assessment (LCA). Other remanufacturing cleaning technology focused papers such as Maharjan et al [17] examines the feasibility of using femtosecond laser as a tool for surface cleaning of aerospace components [17].

While the remanufacturing cleaning has been acknowledged as a "costly operation" [12] within the remanufacturing operations, there has been no study that has captured the embodied energy utilised in remanufacturing cleaning operations relative to the whole remanufacturing process. Investigating this energy is critical, as remanufacturing

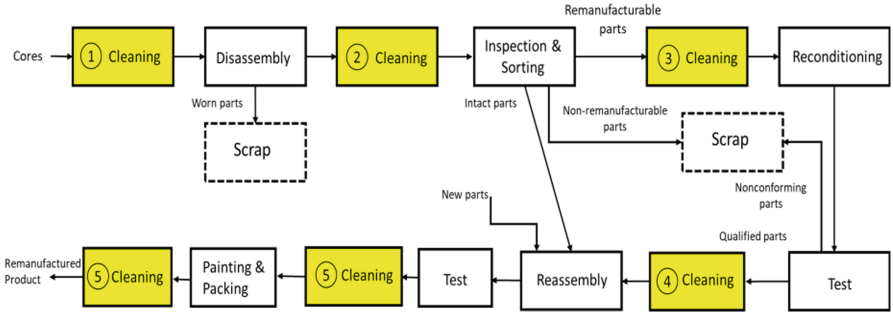



**Fig. 2.** A multistage cleaning remanufacturing flow diagram. Adapted from Liu et al., [15]

cleaning is the foundation for the testing, painting and assembling of waste products and components in remanufacturing. Studies such as Peng et al, identified electricity derived from thermal power plants as the main energy source [7]. This is relevant for cleaning technologies such as supercritical CO2, liquid blasting cleaning, high temperature decomposition and shot blasting. The Embodied energy (EE) concept originates from the theory of systems ecology [18, 19]. EE includes the energy burdens generated across the product life cycle, from the acquisition of raw materials, processing, manufacturing, transportation to site and construction throughout the whole life cycle [20]. It thus captures the total energy use along global supply chains [20]. It reflects the direct and indirect energy requirements throughout the whole supply chain to meet different final demand categories [21, 22]. Multi-regional input output MRIO) modelling have been utilised in calculating embodied energy for buildings, building insulating materials, water footprints, greenhouse gas emission, megacities [19, 20, 23]. While the MRIO model provides a powerful mechanism to examine the intraregional and interregional economic characteristics, it can be applied to identify the resource requirements and energy spillover of products and municipalities [24]. Thus, this study shall achieve two things; First, it shall clarify and map existing remanufacturing cleaning technologies using available literature. Secondly, it shall develop an MRIO modelling framework to investigate the embodied energy of remanufacturing cleaning operation. This is the first study that shall provide a quantitative methodology for calculating remanufacturing cleaning operation and is expected to have both academic and industry contribution.

## References


1. Singhal,D., Tripathy, S., Jena, S.K.: Remanufacturing for the circular economy: study and evaluation of critical factors. Resources, Conservation and Recycling. Elsevier; 156(June 2019): 104681 (2020). https://doi.org/10.1016/j.resconrec.2020.104681
2. Luthra, S., Govindan, K., Mangla, S.K.: Structural model for sustainable consumption and production adoption—a grey-DEMATEL based approach. Resources, Conservation and Recycling. Elsevier B.V., **125**, 198–207 (2017). https://doi.org/10.1016/j.resconrec.2017.02.018
3. Reike, D., Vermeulen, W.J.V., Witjes, S.: The circular economy: new or refurbished as ce 3.0? — exploring controversies in the conceptualization of the circular economy through a focus

on history and resource value retention options. Resources, Conservation and Recycling. Elsevier, **135**(November 2017), 246–264 (2018). https://doi.org/10.1016/j.resconrec.2017.08.027
4. Casper, R., Sundin, E.: Addressing Today's challenges in automotive remanufacturing. Journal of Remanufacturing (2018). https://doi.org/10.1007/s13243-018-0047–9
5. Peng, S., Ping, J., Li, T., Wang, F., Zhang, H., Liu, C.: Environmental benefits of remanufacturing mechanical products: a harmonized meta-analysis of comparative life cycle assessment studies. Journal of Environmental Management. Elsevier Ltd, **306**(December 2021), 114479 (2022). https://doi.org/10.1016/j.jenvman.2022.114479
6. Parker, D., Riley, K., Robinson, S., Symington, H., Tewson, J., Jansson, K., et al.: Remanufacturing Market Study. European Remanufacturing Network (2015). EC--09 404 ERN WP2.2.docx
7. Peng, S., Li, T., Tang, Z., Shi, J., Zhang, H.: Comparative life cycle assessment of remanufacturing cleaning technologies. Journal of Cleaner Production. Elsevier Ltd, **137**, 475–489 (2016). https://doi.org/10.1016/j.jclepro.2016.07.120
8. Feng, Y., Tian, Y., Zhu, Q.: A combined input-output/decision making trial and evaluation laboratory method for evaluating effect of the remanufacturing sector development. Journal of Cleaner Production. Elsevier Ltd; **114**, 103–113 (2016). https://doi.org/10.1016/j.jclepro.2014.10.048
9. Conway, L.: Right to Repair Regulations. House of Commons Library, pp. 1–9 (2021). https://researchbriefings.files.parliament.uk/documents/CBP-9302/CBP-9302.pdf
10. Gutowski, T.G., Sahni, S., Boustani, A., Graves, S.C.: Remanufacturing and energy savings. Environmental Science and Technol. **45**(10), 4540–4547 (2011). https://doi.org/10.1021/es102598b
11. Kerin, M., Pham, D.T.: Smart remanufacturing: a review and research framework. J. Manufacturing Technol. Manage (2020). https://doi.org/10.1108/JMTM-06-2019-0205
12. Gamage, J., Ijomah, W., Windmill, J.: What makes cleaning a costly operation in remanufacturing? In: Seliger, G. (ed.): Proceedings of the 11th Global Conference on Sustainable Manufacturing - Innovative Solutions, pp. 222–226 (2013). http://www.gcsm.eu/Papers/70/7.1_177.pdf
13. Hammond, R., Amezquita, T., Bras, B.: Issues in the automotive parts remanufacturing industry : a discussion of results from surveys performed among remanufacturers. International Journal of Engineering Design and Automation – Special Issue on Environmentally Conscious Design and Manufacturing **4**(1), 27–46 (1998)
14. Sundin, E., Bras, B.: Making functional sales environmentally and economically beneficial through product remanufacturing. Journal of Cleaner Production **13**(9), 913–925 (2005). https://doi.org/10.1016/j.jclepro.2004.04.006
15. Liu, W., Zhang, B., Li, M.Z., Li, Y., Zhang, H.: Study on remanufacturing cleaning technology in mechanical equipment remanufacturing process. Re-engineering Manufacturing for Sustainability (2013). https://doi.org/10.1007/978-981-4451-48–2
16. Liu, W.W., Zhang, B., Li, Y.Z., He, Y.M., Zhang, H.C.: An environmentally friendly approach for contaminants removal using supercritical CO 2 for remanufacturing industry. Applied Surface Science. Elsevier B.V.; **292**, 142–148 (2014). https://doi.org/10.1016/j.apsusc.2013.11.102
17. Maharjan, N., Zhou, W., Zhou, Y., Guan, Y.: Femtosecond laser cleaning for aerospace manufacturing and remanufacturing. Optics InfoBase Conference Papers. Part F122-: 7–10 (2017)
18. Costanza, R.: Embodied energy and economic valuation. Science. **210**(4475), 1219–1224 (1980). https://doi.org/10.1126/science.210.4475.1219

19. Zhang, B., Qiao, H., Chen, Z.M., Chen, B.: Growth in embodied energy transfers via China's domestic trade: Evidence from multi-regional input–output analysis. Applied Energy. Elsevier Ltd; **184**, 1093–1105 (2016). https://doi.org/10.1016/j.apenergy.2015.09.076
20. Grazieschi, G., Asdrubali, F., Thomas, G.: Embodied energy and carbon of building insulating materials: a critical review. Cleaner Environmental Systems. Elsevier Ltd; **2**(January), 100032 (2021). https://doi.org/10.1016/j.cesys.2021.100032
21. Zhang, B., Chen, Z.M., Xia, X.H., Xu, X.Y., Chen, Y.B.: The impact of domestic trade on China's regional energy uses: a multi-regional input-output modeling. Energy Policy. **63**, 1169–1181 (2013). https://doi.org/10.1016/j.enpol.2013.08.062
22. Chen, Z.M., Chen, G.Q.: Demand-driven energy requirement of world economy 2007: a multi-region input-output network simulation. Communications in Nonlinear Science and Numerical Simulation **18**(7), 1757–1774 (2013). https://doi.org/10.1016/j.cnsns.2012.11.004
23. Guo,S., Li, Y., He, P., Chen, H., Meng, J.: Embodied energy use of China's megacities: a comparative study of Beijing and Shanghai. Energy Policy. Elsevier Ltd; **155**(July 2020), 112243 (2021). https://doi.org/10.1016/j.enpol.2021.112243
24. Sun, X., Li, J., Qiao, H., Zhang, B.: Energy implications of China's regional development: New insights from multi-regional input-output analysis. Applied Energy. Elsevier Ltd; **196**, 118–131 (2017). https://doi.org/10.1016/j.apenergy.2016.12.088

# Author Index




S. G. Scholz et al. (Eds.): SDM 2022, SIST 338, pp. 403–404, 2023.
https://doi.org/10.1007/978-981-19-9205-6