Routledge Advances in Production and Operations Management

DIGITALIZATION AND SUSTAINABLE MANUFACTURING

TWIN TRANSITION IN NORWAY

Edited by

Sverre Gulbrandsen-Dahl, Halvor Holtskog,
Heidi C. Dreyer, Einar L. Hinrichsen, Gabor Sziebig,
Håkon Raabe, and Kristian Martinsen

ROUTLEDGE

"*Digitalization and Sustainable Manufacturing* covers research results with a broad view on how digitalization has evolved through eight years as a major tool for transition towards sustainable manufacturing in selected Norwegian manufacturing companies. I recommend this book for readers looking for examples on industry-focused research on digitalization for sustainable manufacturing."

Professor Dr. Ir. Bert Lauwers, *President of the CIRP International Academy for Production Research 2022–2023, and Full Professor in Manufacturing Processes and Systems and Dean of the faculty of Engineering Technology, KU Leuven, Belgium*

"I can recommend this book for its interesting snapshots from manufacturing industry-focused research on how digitalization can serve as a tool in the path towards a more sustainable manufacturing industry. The book offers insights from several areas, encompassing materials and manufacturing processes like additive manufacturing and welding, automation as well as manufacturing systems and organisation."

Professor Michael Zwicky Hauschild, *Co-founder and Director of the DTU Centre for Absolute Sustainability and Professor at the Department of Environmental and Resource Engineering, DTU, Denmark*

Digitalization and Sustainable Manufacturing

The manufacturing industry is facing massive changes driven by digitalization and sustainability. It is being redefined to meet the UN SDGs with the creation of new materials, processes and machinery. The drive for digitalization in order to use resources more effectively and efficiently adds to the complexity of this twin transition. This book presents results from 8 years of research with 15 industry partners, following the transition towards a digitalized industry 4.0 manufacturing and sustainable manufacturing paradigm.

The selected chapters demonstrate how globally competitive manufacturing in high-cost countries such as Norway is enabled by AI-supported intelligent and flexible automation and the use of digital twins, as well as human-centred manufacturing. This book describes the interactions in innovative and sustainable organizations and changes in materials, products and processes, digital twins and AI-supported automated manufacturing processes. Supported by case studies and reflections from the manufacturing industry, this book evaluates how the combination of digitalization and sustainability enables competitiveness. With a focus on multi-material products and processes, robust and flexible automation and innovative and sustainable organizations, it provides a multi-disciplinary insight into the challenges and opportunities faced by manufacturing industries over time.

This book serves as an ideal reference for researchers, scholars and policymakers in manufacturing, production and operations, with a particular interest in technology and sustainability.

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Edited by Sverre Gulbrandsen-Dahl, Halvor Holtskog, Heidi C. Dreyer, Einar L. Hinrichsen, Gabor Sziebig, Håkon Raabe, and Kristian Martinsen

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Preface

Welcome to the book *Digitalization and Sustainable Manufacturing*. In an era of constant uncertainty, rapid technological advancements and a pressing need for sustainability, the intersection of digitization and manufacturing stands as a pivotal point in shaping our collective future.

This book explores the profound impact of different aspects of digitization on the manufacturing sector through the lens of the Centre for Research-Based Innovation Manufacturing (SFI Manufacturing) in Norway. The centre has been a cross-disciplinary research centre over the period 2015–2023, and has been a collaboration between 14 globally competitive manufacturing companies in Norway, Norwegian University of Science and Technology and the research institute SINTEF. The centre has received funding from the Research Council of Norway under their SFI scheme. SFI Manufacturing represents a comprehensive approach to manufacturing research that integrates sustainability principles into manufacturing processes and technology, emphasizing environmental responsibility, economic viability, and social equity.

As we embark on this journey, it is essential to recognize the transformative power of digitization. From advanced data analytics and artificial intelligence to the Internet of Things (IoT) and additive manufacturing, digital technologies offer unprecedented opportunities to enhance efficiency, optimize resource utilization and unlock innovative solutions across the manufacturing value chain.

Throughout the chapters, readers will encounter insightful discussions on various facets of digitization in manufacturing, including:

- Towards sustainable and circular manufacturing
- Barriers and opportunities through digitalization
- Novel manufacturing processes and materials

This book synthesizes theoretical frameworks, practical case studies and industry best practices to provide a comprehensive guide for academics, researchers, practitioners and policymakers interested in advancing sustainable manufacturing.

Ultimately, our holistic approach within the context of SFI Manufacturing promises to enhance operational efficiencies and economic competitiveness and foster a more sustainable future.

We will express our acknowledgement of financial support from the Research Council of Norway and the consortium of SFI Manufacturing. We extend our gratitude to the reviewers who provided excellent comments to the individual book chapters, the contributors whose expertise and dedication have enriched this volume and the readers whose engagement and commitment to sustainable manufacturing inspire us to push the boundaries of innovation and stewardship.

Together, let us embark on this transformative journey towards a digitized future, in which sustainability serves as the cornerstone of manufacturing excellence.

Chapter 1

Introduction

Sverre Gulbrandsen-Dahl, Heidi C. Dreyer, Einar L. Hinrichsen, Halvor Holtskog, Kristian Martinsen, Håkon Raabe, and Gabor Sziebig

Norwegian manufacturing

The Norwegian manufacturing industry is small with a relatively uniform structure. Compared with many other countries, Norway as a small country has a high share of exports and imports, mainly to and from the EU (74% export and 68% import).

Manufactured machinery and means of transport manufactured by the mechanical-engineering industry contributed to around NOK 50 billion of Norway's export revenues in 2019. This includes automotive and aerospace parts, ships, maritime and ship machinery, defence, power and office machinery, as well as telecommunications and computer equipment. Ship exports provide around 25% of the export value of this section of the mechanical-engineering industry. Norwegian manufacturing companies encompass high-volume production as well as high-mix, low-volume specialised production. Many Norwegian companies are globally competitive in their selected niche markets. There are several companies with advanced manufacturing technology and a very high level of automation. Some of these companies were part of the SFI Manufacturing centre.

Research in SFI Manufacturing

This book focuses on manufacturing research in industries where Norwegian companies over the years have adapted to advanced technologies and automation and, by doing this, built strong global competitiveness based on their products, manufacturing processes and effective organisation and management structures. This covers high-value manufacturing companies producing automotive components, high-speed vessels, maritime machinery, tooling, defence products, aeronautic components, sensors and consumer electronics. On average, these companies export more than 85% of their product sales, indicating they have proven international competitiveness in various markets and are regarded as the national team of manufacturers in Norway.

The research covered in the book is organised in a centre for research-based innovation (SFI), which is a strategic instrument applied by the Research

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Council of Norway to develop expertise in fields of importance for innovation and value creation at a national level. The setup of SFI centres, in order to contribute to innovation and value creation, is as research activities over an eight-year time period carried out in close collaboration between research-performing companies and prominent research partners. The vision and aim of the research in the centre is to explore how and why sustainable and advanced manufacturing is possible in a high-cost country and what mechanisms can explain the adoption and transition to digital and sustainable requirements facing globally exposed manufacturing companies. The research is focused on sustainable productivity in manufacturing, particularly hybrid multi-material structures, automation and Industry 4.0 technologies and intelligent and sustainable organisations and manufacturing systems.

The research, which is a close collaboration between 14 highly advanced Norwegian manufacturers, the Norwegian University of Science and Technology (NTNU), and the research institute SINTEF, took place between 2015 and 2023. Over the eight years, the centre has contributed to educating 16 PhDs, 4 postdocs and more than 50 master's degrees. Several industrial R&D projects with substantial innovation potential have been generated and spun off, further increasing the impact of the centre. Together, the partners have published more than 200 scientific peer-reviewed publications at international research conferences and meetings and in international scientific journals. These publications cover the span from atomistic modelling of multi-material joining to knowledge development in geographical clusters, indicating a high standard, quality and relevance of the research in the centre. The presented research in this book is a glimpse of the activity in the centre, all originally written chapters for the book. The chapters, illustrating the span of the activity and the depth of the research, are structured to show how the research has evolved over time and, as such, acted as a strong instrument in fulfilling the aims of the industrial and academic partners. Part I: Sustainable and circular manufacturing. Part II: Barriers and opportunities through digitalisation. Part III: Novel manufacturing processes and materials.

Research approach

The research presented in the book evolves from a cross-disciplinary approach to manufacturing research, combining disciplines of multi-material and processing science, automation and robotics in manufacturing systems, and organisation and management science. High-value manufacturing is a complex sociotechnical system involving technical and social systems and subsystems. To understand the impact of the interactions in the sociotechnical system in the particular manufacturing context of the industrial partners, a multidisciplinary approach is needed.

Three areas categorise the research in the book: multi-material products and processes, robust and flexible automation, and innovative and sustainable organisations. The priorities within these three areas have developed over the centre period in a cocreation process between industry partners and academic partners. An example of this development is the change from descriptive research to scenario-based research within the sociotechnical approach within sustainable originations, with more focus on developing tools for supporting strategic decisions in organisations. An additional example is the sustainability focus that has gained considerable attention over the last three to four years of the centre period, and it is interesting to note that sustainability was not in the described core of research at the centre start. The development of the thematic focus of the industrial partners over the centre period is analysed and presented in the section Research topics of interest and discussed in the context of how the topics have influenced the centre research and development of spin-off activities such as innovation projects.

Research topics and questions were identified mainly by combining literature and practice according to a systemic combining approach (Dubois and Gadde, 2014) to maintain the academic and empirical relevance and robustness of the research. This sprung out of dialogues and input from the industrial partners (identified problems and need for knowledge) that took place in multiple fora and forms, such as 1-1 meetings (which were yearly strategic meetings between industry executives and centre managers), regular research workshops between industrial partners and researchers (three to four times a year) and throughout multiple research projects and case studies. The research activity has been organised as PhD and post-doctoral projects, innovation and competence-building research and master’s thesis projects.

Research topics of interest

The strategic 1-1 meetings with each of the industrial partners were performed once a year, primarily in the beginning of the year to align with the research plan. SFI centre management members were always present, and frequently additional researchers from the academic partners participated as well. A total of 17 industrial partners have been involved, most of them during the whole centre period. All meetings were held at the premises of the company, except for the meetings during the pandemic; that is, most of the meetings in 2020 and all in 2021.

A total of 120 meeting minutes have been taken, almost all of them in Norwegian. In all these meetings with the industrial partners, strategic challenges and topics of interest within the broader area of manufacturing have been discussed. These minutes form a fairly large amount of text, around 36,000 words. To condense how these discussions and topics of interest have developed during the centre period, it was decided to try out AI in the form of the large language model Chat GPT, which was launched late in 2022. The 3.5 version (as of September 25, 2023) was used, also because this version of the model stated it no longer added new prompts to the model. It was important not to share any more information than was necessary. Further, it was taken into account that large language models in general are not fully reliable when asking specific questions on scientific topics, but in this case, a large language model was used for what it is good at: making summaries of large texts and listing the main topics in them.

The process was carried out as follows: First, the individual meeting minutes were generalised, removing specific references to companies or persons. Then, each generalised meeting minute text was copied into Chat GPT, asking it to translate it into English and making a summary. In the same chat, this was repeated for each company meeting minutes for that specific year. At the end of the chat, Chat GPT was asked to list the main topics across all the previous summaries. This was then repeated for all the consecutive years. Each chat was deleted as an extra precaution, but the produced summaries were copied to a summary spreadsheet that also holds the original texts.

Chat GPT was not specifically asked to list the topics in a prioritised or ranked order. However, the list sequence was kept and generally matches the impression of importance from year to year. The list of topics per year was used to manually generate shorter keywords representing the main topics from the 1-1 meeting discussions per year. Specific topics around centre project organisation and collaboration were removed to focus on broader strategic and academic issues. Since the authors of this chapter had participated in the meetings, a simple quality check was to see whether the lists matched the impressions of the meetings per year. Previous executive summaries of some yearly 1-1 meeting rounds allowed a further check of the quality of the Chat GPT-generated topic lists. It should be noted that the topics of the 1-1 meeting discussion were not driven by the companies alone. The researchers also participated actively and were part of forming the topics and matters discussed. As such, the following lists represent a topical development within a consortium of industrial companies and academic institutions within manufacturing.

In Figure 1.1 below, the keywords from all the 1-1 meetings as described above are listed per year.

2015	2016	2017	2018	2019	2020	2021	2022	2023
Multimaterial products and processes	Digitalisation, additive manufacturing	Production technology and automation	Automation and robotics	Automation and product complexity	Digitalisation and automation	Production process optimisation (Ind. 4.0)	Sustainability and green initiatives, circular economy	Sustainability and circular economy
Flexible automation	Materials and manufacturing processes	Material technology, Material science	Materials and multimaterial processing	Sustainability and environment	Sustainability and Circular Economy	Sustainability and environment	Automation, robotics and digitalisation	Digitalisation and Industry 4.0
Organizational processes	Workforce and organisational challenges	Process improvement	Digitalisation and Industry 4.0	Additive manufacturing, Industry 4.0	Materials and manufacturing methods	Reshoring and global supply chains	Material choices and quality control	Materials and manufacturing processes
Efficiency and Lean practices	Quality and optimisation	Training, Knowledge building	Sustainability and environment	Data and Digitalisation	Additive manufacturing	Materials and material processing	Global operations geopolitics and pandemics	Energy and resource management
Metallurgy	Industry 4.0 and automation		Additive manufacturing	Process optimisation, quality, cost, efficiency	Product and process innovations	Automation and digital transformation	Implementing new technologies	Global value chains and complexity
				People and skills		Cybersecurity and data protection	Human capital, Talent development	
						Quality control and traceability		

Figure 1.1 List of topics per year from company 1-1 meetings.

As the figure shows, several of the same (broader) topics appear multiple times, although they use slightly different words. How, then, have the discussions developed? To illustrate this, the following grouping of topics was made manually to generally match how the research activities in SFI Manufacturing have been grouped.

Materials and processing

Materials and processing were major research areas throughout the whole period, as shown in Figure 1.2.

The figure clearly shows how this topic has been present and important throughout the project period, although it shows up slightly lower on the list towards the end of the centre period. In the early years, multi-material products, designs and processes were underlined in areas such as the joining of dissimilar materials. Later, there is increasing interest in material selection, properties, processing and handling. Towards the end of the period, the focus is on materials with lower environmental footprints, combined with the effect these new or changed materials have on the manufacturing processes. Disassembly and recycling of materials now get just as much attention as joining.

Additive manufacturing

Additive manufacturing (AM) has been an important topic in the research, and Figure 1.3 shows how this topic has been present in the 1-1 meeting discussions and summaries of meetings. In the early years, AM was discussed more as a new and promising production technology, while further out in the centre period, it was more a question of applicability and where AM was best suited.

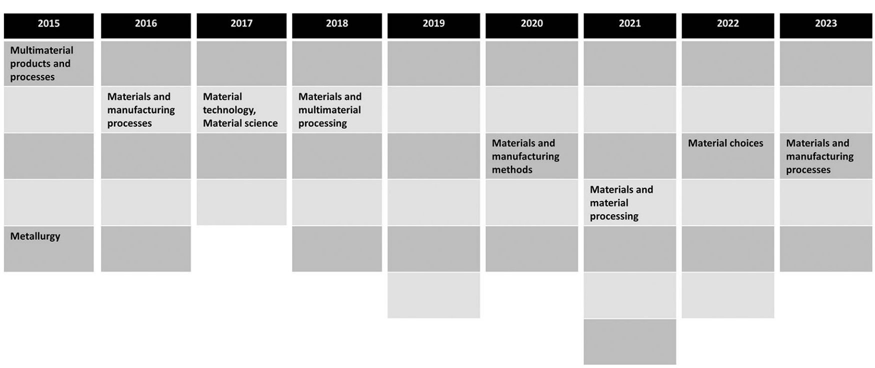

Figure 1.2 Materials and processing topics per year.

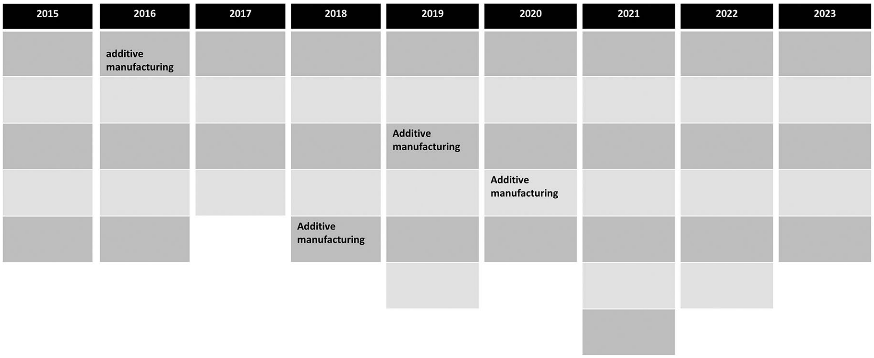

Figure 1.3 Additive Manufacturing topics per year.

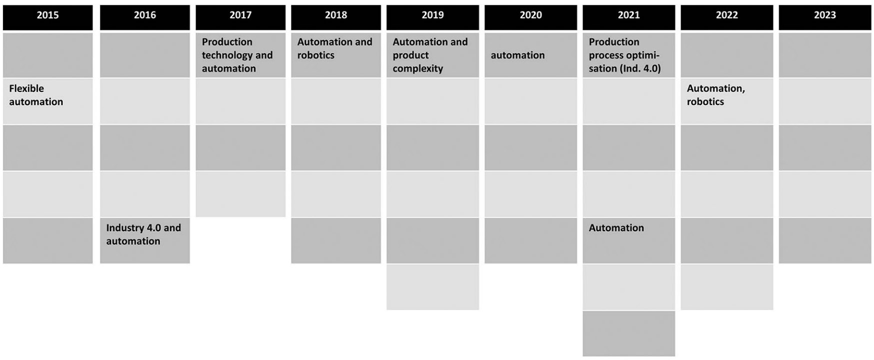

Figure 1.4 Automation and robotics topics per year.

Automation and robotics

Production technology in the form of automation and robotics has been another major research area, as is evident from Figure 1.4.

Flexible automation has been important right from the start, and the need for adaptivity has been underlined, e.g., in the form of integrating different kinds of sensors. The use of robots not only for material handling but also for processing and assembly has seen keen interest. Later, more interest was noted in implementing complex automated production processes, as well as seeing robotics and automated production as part of a broader digital transformation, or Industry 4.0, as it was commonly termed.

Digitalisation

This broad topic has spanned two of the research areas. The topic of flexible automation and robotics has primarily focused on production processes and

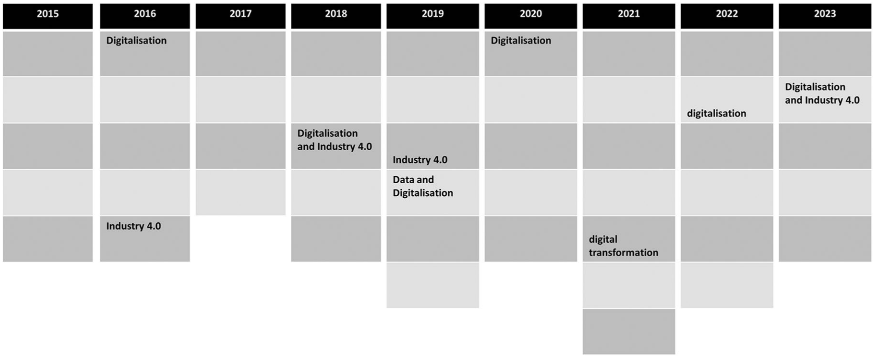

Figure 1.5 Digitalisation topics per year.

is clearly a part of digitalisation. However, digitalisation and Industry 4.0 have also been major parts of the research on manufacturing organisations and value chains. Figure 1.5 shows how this topic has appeared during the 1-1 meeting discussions.

In the beginning of the research, discussions on digitalisation and Industry 4.0 focused on topics like data capture, visualisation, and monitoring of processes for quality control. Later, the companies were increasingly interested in data-driven decision-making, digitalisation and the potential of big data in improving their operations. Also, exploring ways to incorporate digital tools, monitoring and online process control to enhance efficiency and productivity was addressed as needed knowledge by the partners. Towards the end of the research period, digitalisation and Industry 4.0 are still recurring themes, reflecting the importance of technology, data and automation in improving efficiency and – to be noted – sustainability in manufacturing and operations.

Organisation

As noted at the start of this chapter, one of the research areas has been sustainable and robust organisations. When meeting the industrial partners, organisational issues have been a natural part of the discussions. Figure 1.6 shows how this topic has appeared in the 1-1 meeting over the years.

In the beginning, companies saw the importance of enhancing organisational processes, knowledge dissemination and innovation integration. Later, knowledge needs addressed by the industry partners were related to workforce development, changing job roles and the need for an adaptable and skilled workforce. Towards the end of the period, the focus shifted more towards challenges in implementing new technologies, human capital and talent development, as well as exploring new business models.

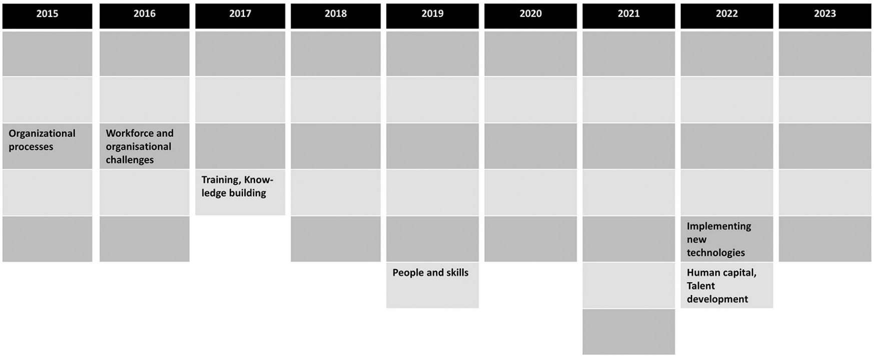

Figure 1.6 Organisation topics per year.

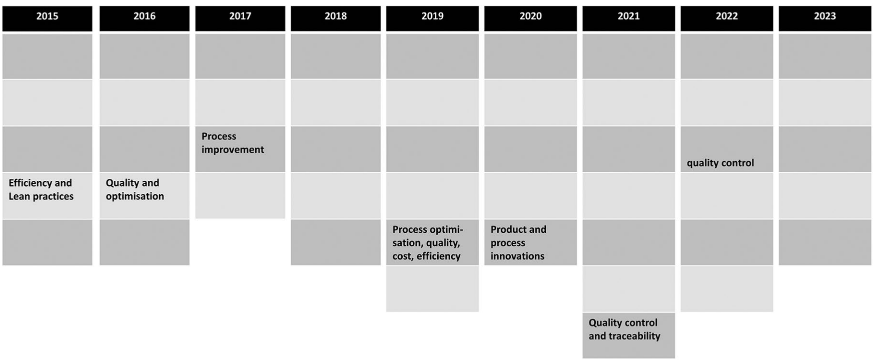

Figure 1.7 Lean and QC topics per year.

Lean and quality control

Despite automation and robotics being core research areas, the industrial partners have underlined the importance of lean, continuous improvement and quality control in increasing productivity and securing profitability. Figure 1.7 shows how these topics have appeared in the 1-1 meetings.

In the beginning, the focus was to streamline the production processes, improve efficiency, and incorporate lean principles. Quality control, process optimisation, and product quality were key considerations for many companies. Later, increased interest in using digital tools and monitoring processes for quality control became evident. Quality control and traceability saw increased interest, including one-piece tracking, tracing and verification solutions within value chains. Towards the end of the centre period, lean activities and digital transformations were seen as complementary to streamline production processes. Companies also note challenges in integrating new technologies into their manufacturing processes and ensuring they meet quality standards.

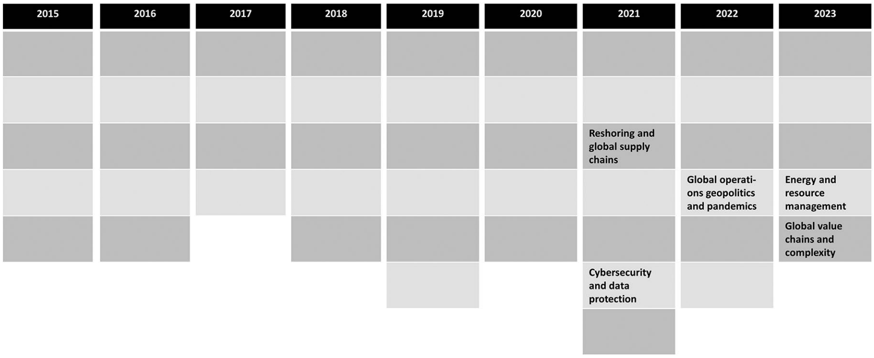

Figure 1.8 Global challenges and topics per year.

Global challenges

The manufacturing world has seen several disturbances during the centre period. In early 2020, the COVID-19 pandemic caused sudden and drastic changes, not only in the way the centre participants worked and interacted but also how lean and global supply chains were hit and disrupted. Later, war in Europe and geopolitical issues became very important factors in manufacturing. Figure 1.8 shows how these issues appeared in the 1-1 meeting discussions.

Naturally, these issues were not present in the early years of the research. In 2020, the 1-1 meetings were held right before and right after Norway closed down due to the COVID-19 pandemic. Some companies reported short-term production effects, but the more long-term impacts were not discussed at that stage. In 2021, the world looked quite different, and challenges in global supply chains and the consideration of reshoring manufacturing activities were discussed. Also, there was a raised awareness of the importance of cybersecurity and data protection due to cyber threats and data breaches within the manufacturing industry. The year 2022 saw the Russian invasion of Ukraine, and meeting discussions underlined the impact of global events, such as geopolitical issues and pandemics. Finally, in 2023, again driven by global events, topics like energy consumption and resource availability were prevalent concerns in the 1-1 meetings. The complexities of managing global value chains, manufacturing processes and logistics were highlighted in this year's meetings.

Sustainability

As noted initially, sustainability was not a key research area when the centre period started in 2015. It should be noted that some companies have already talked about the need for improved sustainability in their products and the adoption of sustainable and eco-friendly technologies, but mostly in the

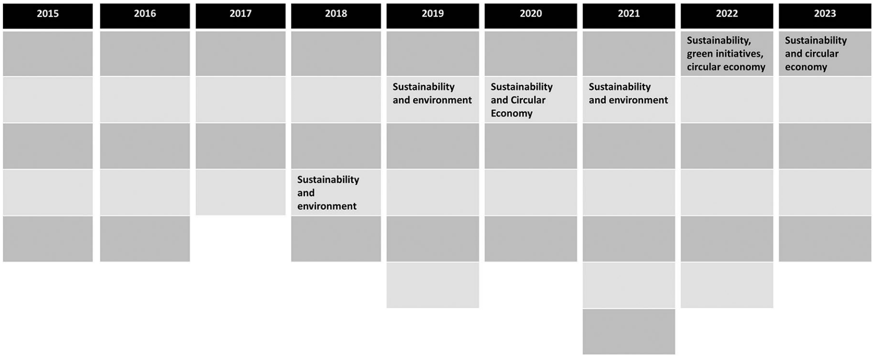

Figure 1.9 Sustainability topics per year.

frame of materials and manufacturing processes. In 2018, some companies were concerned with sustainability, circular economy concepts, reducing their environmental footprint, discussing issues like recycling, reusing materials and energy efficiency. Figure 1.9 clearly shows how this topic has gained interest and, towards the end of the research period, has become maybe a major issue for the industrial partners.

Later, sustainability, environmental impact, green initiatives, and circular material flows were recurring themes, with companies looking to reduce material costs, explore recycling or reuse and address sustainability challenges in their industries. They were considering the environmental impact of their activities as well as the potential for using recycled materials in their products and processes. The focus was on reducing carbon footprints through the exploration of more sustainable materials, recycling and energy-efficient practices.

At the end of the research period, topics like transitioning to a circular economy focusing on reuse, recycling and sustainable practices appeared in the 1-1 meetings. Sustainability efforts and circular economy concepts became top issues, and companies were working on reducing their environmental impact, increasing recycling and reusing materials and exploring ways to integrate sustainability into their operations.

Closing this overview of topics discussed during the 1-1 meetings with the industrial partners, Chat GPT wraps up the 2023 summaries in the following way: “These topics collectively reflect the diverse interests and activities of the companies involved in the research, showcasing their efforts to balance economic growth with environmental sustainability and technological innovation.”

The world of materials and manufacturing is seeing important changes. Sustainable manufacturing must be based on recycled materials, reuse of parts and remanufacturing. Effective and automated processes must also be robust and flexible and tolerate large variations in materials, qualities and components. There is a need for new design and product development methods, new processes and use of additive technologies, new circular business models, automation of disassembly and effective return logistics and digital platforms for information sharing and tracing in a circular manufacturing system.

Reflections on topics covered

The topics covered in the previous section are based on the meeting minutes – turned into summaries – from the 1-1 meetings with the industrial partners. They are not derived from the different PhD projects. Nor are the topics drawn directly from the industrial workshop themes that had a clear connection to the three research areas noted in the beginning; materials and processing; robust and flexible automation; and sustainable and robust organisations. However, the topics do generally align with these research areas.

The chapters included in this book cover a broad range of topics. Further, they reflect the topics derived from the 1-1 meetings with the industrial partners: Part I, "Towards sustainable and circular manufacturing," covers the topic of sustainability as well as some of the global challenges. Part II, "Barriers and opportunities through digitalisation," covers the topic of digitalisation and touches on the topics of AM, organisation, lean and quality control, as well as some of the global challenges. Part III, "Novel manufacturing processes and materials," covers the topics of materials and processing and automation and robotics, as well as AM.

Concluding this introduction, it is our hope as editors that the reader will also find that most of the topics derived from the yearly 1-1 meetings with the industrial partners are covered in the chapters to follow.

Towards sustainable and circular manufacturing

Chapter 2

A novel circular manufacturing assessment method for the aluminium industry

Paul Kengfai Wan, Giuseppe Fragapane, Helene Øyangen Lindberg, and Marit Moe Bjørnbet

Introduction

Aluminium is a popular and widely used metal in several industries, such as automotive, manufacturing, and clean energy technologies, due to its lightweight and strong properties [1, 2]. Efforts to reduce the weight of vehicles in the automotive industry depend highly on aluminium, as a core component, to improve both fuel consumption and carbon dioxide emissions. Although extensive research efforts have been made to reduce the energy consumption in primary production, the melting of aluminium [3], it still consumes high amounts of energy and is responsible for approximately 3% of global greenhouse gas emissions in 2021 [4].

The recyclability of materials and products has become increasingly relevant considering recent years' flourishing of the circular economy (CE) as a concept in the manufacturing sector due to the potential benefits. CE is about closing resource loops through "reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes" [5]. Kirchherr et al. [5] also emphasize that CE solutions should contribute to environmental, social, and economic sustainability. For example, aluminium is being recycled not only because of the high content of aluminium in different scrap sources but secondary production (re-melting of used aluminium) also has potential environmental benefits because it is estimated to consume up to only 1/5 of the energy of primary production [6].

Potting et al. [7] provide a 10 R-strategies framework, ranging from zero to nine, based on their contribution to circularity. They recommend that businesses focus their efforts on the more circular R-strategies (e.g. R0–R6). In addition to recycling (R7), the aluminium industry can adopt other R-strategies such as reuse (R2) or remanufacturing (R5) to enhance circularity. Despite the rule of thumb (lower R's means more circular), all CE efforts should be assessed to avoid shifting environmental burdens or circular washing (i.e. circular practices that provide little improvement of the overall environmental footprint).

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There are different assessment methods to evaluate and measure circularity [8]. Life cycle assessment (LCA) is a well-established method for addressing the environmental impacts of products and services and is also one of the most commonly used methods for assessing CE [8, 9]. It is primarily applied at the product level but can also adopt a macro-level approach when supporting decisions related to national policies or sector strategies for technologies, services, or product portfolios. However, it is not an appropriate tool to assess the performance of the global economy, while other tools such as material flow analysis (MFA) would be more appropriate [10]. While there are efforts in assessing the circularity of aluminium, particularly recycling, there is no assessment that prioritizes other types of R-strategies that can help practitioners evaluate and enhance the circularity of their aluminium materials and products.

In this work, we aim to develop a novel circular manufacturing assessment method for the aluminium industry, enabling companies to set their baseline, explore, and compare different options for shifting towards more circular operations. In order to develop a feasible and adequate assessment method, we combine both a systematic literature review to obtain a clearer overview of the current state of the art of circular assessment in the aluminium industry and workshops with industry experts to provide actual industry practice and knowledge to make our assessment method more robust. The following research questions (RQs) will guide this study:

- RQ 1: What is the current state of practice in evaluating the circularity of aluminium value chains?
- RQ 2: How should the circularity of aluminium value chains be evaluated?

This paper is structured as follows: Section "Theoretical background" provides a theoretical background on circular assessment methods. The research methodology for the systematic literature review and workshops is outlined in Section "Methods". Section "Current state of practice in evaluating circularity in the aluminium industry" provides the results of the current practices in evaluating circularity in aluminium value chains. Section "Method to evaluate circularity in aluminium value chains" introduces an overall framework of circular pathways and outlines the novel circular assessment methods. An example use case is also explained in this chapter. Section "Discussion" discusses the assessment methods; finally, we conclude in Chapter 7.

Theoretical background

Aluminium is a material that has the potential to move towards CE. In addition to recycling, other strategies focus on different phases of a life cycle, which can bring actual benefit to the industry. For example, strategies that begin in the early design phase with a focus on sustainability, energy, and material efficiency during the operation phase and finally the end of life of the material [11]. Circular assessments are often deployed to measure the circularity of the applied strategies, but they are not yet a common practice in companies [9]. One of the reasons could be that both companies and policymakers do not know where to begin with or are not familiar with CE [8].

Social, environmental, and economic sustainability are the three common pillars to assess the circularity in production, but it is also important to assess the circularity from within the manufacturing process itself. This is because every manufacturing process is unique, and any direct application of existing circularity assessments to industries can lead to confusion and may fail to capture the benefits of such assessments [8]. Currently, we have not identified any circular assessment focusing on the manufacturing industry itself, specifically the aluminium industry, to assess the circularity. Most of the existing circularity assessments have been criticized for not representing the collaborative nature of different stakeholders in the entire value chain of an industry [12]. Thus, research that focuses on the multidisciplinary nature of aluminium manufacturing perspective is needed.

LCA can be combined with other circular assessment methods, such as the MFA and material flow cost accounting, to assess the material and economic aspects of the entire life cycle. For example, [13] combine LCA with real estate appraisal and economic evaluation of project environmental design and develop a conjoint "economic-environment indicator" that assesses both economic and environmental aspects in the construction sector with special attention to the end of life. Methods to measure the circularity of processes and products have been introduced by policy developers, scholars, and businesses [8]. For example, LCA, multiple criteria decision making (MCDM), and Design for X can assess how well the principle of CE is applied to a product or process. However, most of the published work focuses mainly on measuring to what extent material cycles are closed and often overlooks the characteristics of the circular loops (e.g. shorter or longer loops) and the multi-dimensional sustainability performance, i.e., environmental, economic, and social [8].

Saidani et al. [12] highlight the current circular assessments do not represent the systemic and multidisciplinary nature of the CE of the industry. Practitioners are experiencing difficulties in improving circularity in the aluminium industry, and essential aspects of circularity in aluminium value chains are also missing in the current assessment methods. Therefore, this study wants to close the gap by reviewing the literature and developing a novel circular manufacturing assessment method for aluminium value chains.

Methods

A two-step research approach was designed and applied by the authors to develop a circular manufacturing assessment method for the aluminium supply chain. The first step was to conduct a systematic literature review to explore the current state of the art of the circular assessment method within the aluminium industry. The second step was to obtain inputs from industrial experts to share their experience and knowledge through workshops to develop a circular manufacturing assessment method that is closer to the industrial setting.

Step 1: Search strategy

The goal of a systematic literature review is to facilitate theory development, align existing research, and discover areas where additional research is needed [14]. The systematic literature review was conducted using Scopus to provide a wide coverage of published literature. The reporting of this review was guided by PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta Analysis Extension for Scoping Reviews) [15]. To identify relevant literature, the search was performed on "Title, abstract and keywords", with Term listed in Table 2.1.

In our search, we focus on peer-reviewed articles, conference proceedings, and review articles to provide a wider overview of circular assessments in the aluminium industry. Only publications in English were considered. Over the last few years, there have been numerous reports produced by businesses, non-governmental organizations (NGOs), and governments. However, they were not included in our search to avoid the potential discrepancies between the motivations and results found in commissioned reports. Those organizations might be prone to present success stories rather than implementation failures [16]. The systematic literature review process flow is summarized in Figure 2.1.

Step 2: Workshops with industrial experts

Two workshops were organized to review the results and complement the limitations of the systematic literature review. The workshop also aims to refine the circular manufacturing assessment method for the aluminium industry. The participants have an international and industrial background and expertise, as shown in Table 2.2. They are primarily located and working

Table 2.1 Search words for the systematic literature review

Term 1	*Term 2*	*Term 3*
Circularity **Circular economy**	Assessment Indicator Performance	Aluminium

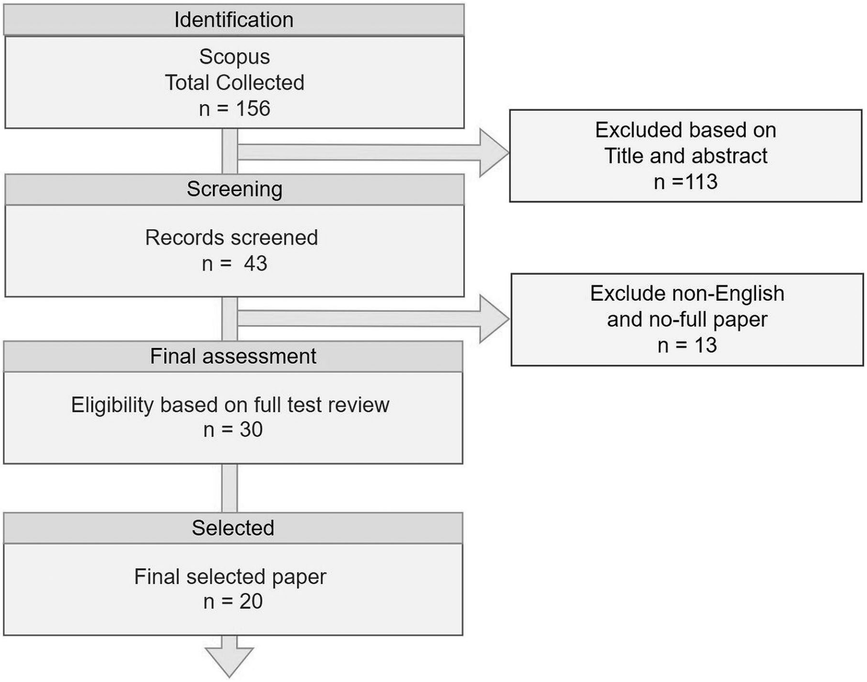

Figure 2.1 Literature review process flow.

Table 2.2 Overview of the workshop participants

Workshop	*Participants from primary or secondary production*	*Participants from parts or product manufacturing*	*Participants from companies associated with waste management (sorting, transportation, etc.)*	*Participants from universities or research centres*	*Participants total*
1	12	10	8	17	47
2	4	10	4	21	39

in Norway with international manufacturing facilities, and they are collaborating on circular supply chains.

In the first workshop, the results of the literature review were presented and discussed with experts from academia and practitioners in the aluminium industry. The main material flow, barriers, and enablers of the circular manufacturing assessment are reviewed and discussed in the first part of the workshop. The first version of the circular manufacturing assessment method for the aluminium industry was introduced in the following workshops. The participants were separated into smaller groups to test, discuss, and provide feedback on the assessment. The discussion supported the literature review results more in depth and improved the circular manufacturing assessment method.

The second workshop was to revise the circular manufacturing assessment method by presenting it to a broader audience from both the aluminium and metal industries. The feedback improved the circular manufacturing assessment method (presented in Section "Method to evaluate circularity in aluminium value chains").

Current state of practice in evaluating circularity in the aluminium industry

Based on the systematic literature review, 20 articles describing different assessment methods were selected and analysed (summarized in appendix). Table 2.3 shows the categorization of the articles based on circular assessment methods and indicators.

More than half of the collected studies use LCA to analyse and evaluate the circularity of aluminium value chains. Some of the studies combined LCA with MFA to map material streams and evaluate the environmental impact. Some studies use experiments and simulations to develop a material flow stream. Low et al. [23] describe a modelling approach for closed-loop production systems called Product Structure-based Integrated Life cycle Analysis (PSILA). This approach is to provide granularity for analysing different systems, capture the different subsystems processing modules, components, and materials, and reflect closed-loop relationships from material recycling, component and module reuse, or remanufacturing. The PSILA technique streamlines the modelling of closed-loop production systems, especially when dealing with issues like coproduct allocation, which arise with the increase in the number of parts that can be recovered. The goal is to make the carbon footprint modelling and analysis of closed loop production systems more accurate.

In a CE context, the economic benefits and added values for society and the environment must be taken into consideration. Life cycle costing (LCC) is also another assessment used in some of the studies to provide a comprehensive understanding of the impact of the product or service by looking into the direct costs involved. Linear business models concentrate on single-life cycle profits. Assessing the cost-profit performance across multiple life cycles can provide guidance to managers and aid in evaluating benefits, leading to a shift towards circular value chains [18].

The three main suggested circularity indicators are environmental impact, financial impact, and recycle rates, as shown in Table 2.3. Niero and Olsen

Table 2.3 Summary of the circular assessment and metrics from the collected literature

Authors	*Circular assessment methods and R-strategies*				*Circular indicators*		
	LCA, LCC	*MFA*	*Experiment/ Simulation*	*10 R*	*Environmental impact*	*Financial impact*	*Recycle rates*
Charpentier Poncelet et al. [17]	X	X		Recycle	X		
Albuquerque et al. [18]	X			Recycle	X	X	
Fellner et al. [19]		X		Recycle, recover	X		X
Niero and Olsen [20]	X		X	Recycle	X		
Sevigné-Itoiz et al. [21]	X	X		Recycle, recover	X		
Haupt et al. [22]		X		Recycle			X
Low et al. [23]	X		X	Reuse, remanufacture, recycle	X		
Stotz et al. [24]	X			Recycle, recover	X		
Nishijima et al. [25]			X	Repair		X	
Moraga et al. [26]	X	X		Reuse, refurbish, recycle, recover	X		
Ghisellini et al. [27]				Recycle, recover	X		
Czerwinski [28]			X	Recycle, recover		X	
De Meester et al. [29]	X	X		Rethink, reuse, repair, recycle, recover	X		
Díaz-Ramírez et al. [30]	X			Recycle	X		
Morgan et al. [31]	X			Reuse, recycle	X		
Hertwich et al. [32]	X			Rethink, reduce, reuse, recycle, recover	X		

(Continued)

Table 2.3 (Continued)

Authors	*Circular assessment methods and R-strategies*				*Circular indicators*		
	LCA, LCC	*MFA*	*Experiment/ Simulation*	*10 R*	*Environmental impact*	*Financial impact*	*Recycle rates*
Niero et al. [33]	X			Recycle	X		
Zink et al. [34]			X	Recycle		X	
Wang et al. [35]	X			Reduce Recycle	X		
Niero et al. [36]	X			Reduce Recycle	X		

[20] argue that simplification in LCA hinders its potential to measure the environmental performance of products in CE scenarios, which require analysis of multiple material loops. Niero et al. [36] highlight that a challenge for LCA in CE is to consider the material loops and accurately quantify the benefits of recycling, including substitution and downgrading factors. Despite these limitations, analysing multiple loops in LCA can provide a better understanding of environmental impacts and support decision-making to enhance circularity.

The European Commission's CE action plan includes targets such as recycling and reusing materials (10 R-strategies) to increase waste management's contribution to the CE. Haupt et al. [22] suggest that a harmonized indicator is needed for comparison among states or regions, and recycling rates based on the input into the last production step are discussed. However, this approach misses incentives to increase the efficiency of recycling. Recycling rates are proposed as a measure and indicator for comparison between countries, as they include the recycling process, provide incentives to optimize all processes, and provide information about secondary materials produced from waste. There are 10 R-strategies that can be adopted to move towards circularity in the aluminium industry [7]. However, based on the collected studies, recycling, recovery, and reuse are the most employed strategies in the aluminium industry, as shown in Figure 2.2. Only 1 study each focuses on reduce (R2), repair (R4), and remanufacture (R6) strategies.

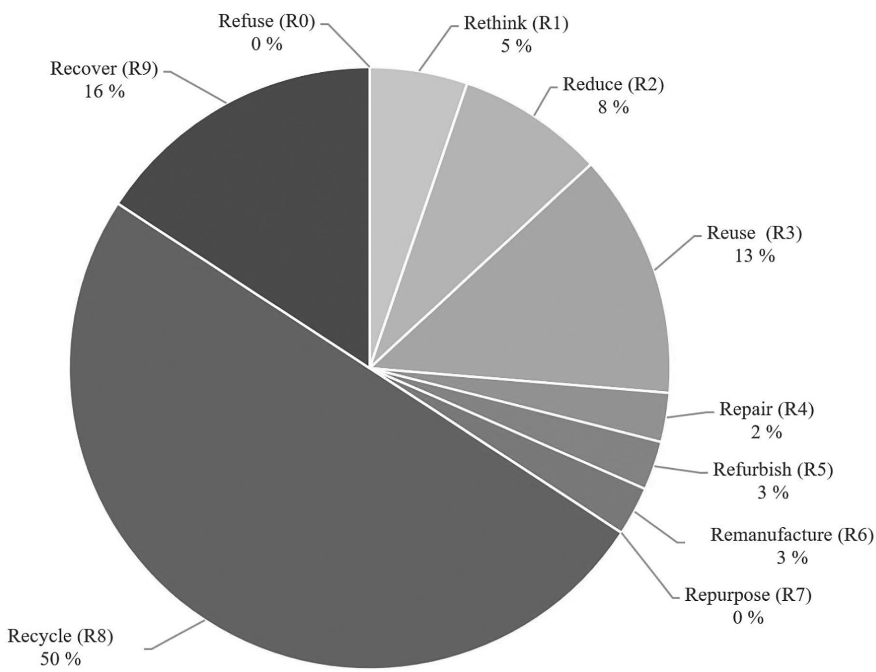

Figure 2.2 R-strategy distribution of the investigated articles.

Data for analysing product and material streams using recycling (R8) and recovery (R9) strategies can be obtained from domestic waste reports and statistics from different countries or from waste export trade data of international waste streams. While data for R-strategies (R0 to R7) are often not linked to public data because the substitution of materials or prolonged product life is not registered and tracked to the same extent on a systemic level compared to recycling and recovery, this results in difficulty in performing data analysis and documenting performance on a meso and macro level with other R-strategies in the aluminium industry.

Compared to recent literature on circular assessment methods and metrics, aluminium value chains primarily use common methods, particularly LCA, but lack diversity, such as input-output, data envelopment analysis [9]. Their strong focus on recycling leads to metrics that focus on the degree of recycled materials, which is commonly used to evaluate circularity and environmental impact with LCA methods [8]. However, these metrics do not consider important aspects of circularity, such as extending product lifetime or designing for circularity. Therefore, assessment methods for aluminium value chains should prioritize alternative 10 R-strategies besides recycling, thereby promoting their adoption.

Method to evaluate circularity in aluminium value chains

This section introduces an overall framework of circular pathways to provide a structured outline to better describe the assessment method, evaluation criteria, and metrics. This section also discusses the primary barriers and enablers for implementing circular practices within the aluminium industry identified during workshops. Key points for enhancing the transition towards circular value chains are highlighted.

Framework of circular pathways in the aluminium value chains

The circular pathway framework was developed through a systematic literature review and was subsequently refined in collaboration with industry experts to ensure its relevance in real-world industrial settings. Figure 2.3 illustrates the framework, delineating the various pathways and stages used to assess circularity within aluminium value chains. These stages encompass (i) primary and secondary aluminium production, (ii) design, (iii) manufacturing, (iv) distribution and usage, and (v) collection, sorting, and transportation. They collaborate to promote circular pathways, reducing the need for extraction, landfill disposal, and incineration.

In Stage (i), the remelting of waste in primary and secondary aluminium production can greatly reduce the extraction of aluminium raw materials.

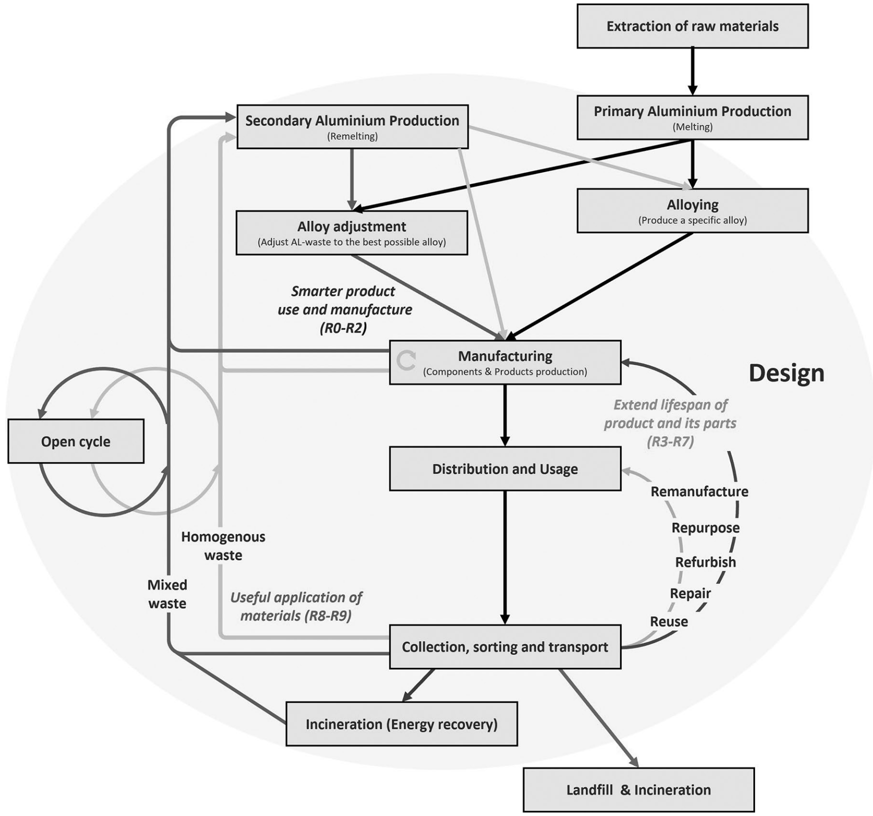

Figure 2.3 Circular pathways in the aluminium value chains.

The quality of the waste must be considered [37] because it has a strong impact on the downcycle, recycle, or upcycle of alloys. For example, in the automotive industry, car components are constructed using various aluminium alloys. Some parts containing high levels of zinc (such as bumper alloys) can greatly hinder the ability to recycle the melt for use in components made of 2xxx, 5xxx, or 6xxx alloys [38]. Remelting of waste materials can result in either a blend of aluminium waste to the best possible alloy or sorted aluminium waste that allows for the production of specific high-quality alloys.

In Stage (ii), the design of products and materials has an impact on the usage of waste materials or circular parts and on the efficiency of circularity. Product design can prepare for circularity through material documentation and ease of disassembling, which eases the sorting and identification of circular potential in the value chain [29].

Manufacturing technologies can use a higher degree of waste material in their manufacturing Stage (iii) yet achieve high product quality.

Manufacturing companies can adopt R-strategies like reuse, repair, refurbish and remanufacture parts and products to increase circularity. Moraga et al. [26] concluded that both refurbishment and reusing aluminium components from laptops have a strong improvement in resource efficiency compared to recycling. They also highlighted that the reuse of laptops showed a carbon emission resource efficiency improvement as high as 157% for aluminium in relation to the baseline.

Advanced technologies and methods can support the identification of circularity potential in Stage (v): collection, sorting, and transport. It can increase the use of remanufacturing (R6), repurposing (R7), refurbishing (R5), repairing (R4), and reusing (R3) strategies and create homogenous waste streams that can increase the upcycle of aluminium waste. Finally, aluminium waste from open cycles needs to be considered in the circular value chain. Waste streams from other products and parts are often neglected in MFA. The circular framework shows different pathways in different stages, but it is important to have a method to assess different circular pathways in each value chain stage.

Circular assessment method in the aluminium value chains

The circular value chain pathways at various stages can be assessed using different criteria and metrics outlined in Table 2.4. This allows for the establishment of a baseline and identifies areas for improvement. Table 2.4 describes the chosen assessment criteria and metrics for evaluating circular value chains, which allow for the comparison of various pathways and the determination of their circularity level. Circular value chains should strive to excel in all these areas.

An exemplary use case

We present a practical case study to exemplify the potential applicability of the circular manufacturing assessment method within the aluminium industry. This case study involves a three-tiered aluminium value chain, encompassing both upstream and downstream partners: the aluminium producer, the manufacturer, and the entity responsible for collecting and sorting aluminium waste. While the products and components within this value chain predominantly employ recycled aluminium, they encounter challenges in progressing beyond recycling and adopting more sustainable strategies (referred to as "R-strategies").

To gain insights into their current operational status and the extent of circular processes in place, the partners in this use case employ the circular manufacturing assessment method, applying the criteria outlined in Table 2.4. Through this assessment, the participating companies realize that the materials used in their products are prone to downcycling at the aluminium producer stage, resulting in their incorporation into lower-value

Table 2.4 The criteria and metrics for the circular value chain stage

Circular value chain stage	*Assessment criteria*	*Assessment metric [%]*
(i) Primary/ secondary aluminium production and alloying	Recycling degree	All aluminium waste/all aluminium production
	Waste stream distribution	Proportion of alloying, only remelting, alloying adjustment (best to worst option)
	Efficiency of producing a specific alloy	Percentage of remelted waste
	Efficiency of adjusting AL waste to the best possible alloy	Percentage of remelted waste
(ii) Design	Proportion of circular components in the product	Recycled, repurposed, remanufactured, repaired, or reused aluminium components/all aluminium components
	Proportion of circular materials in the product	recycled aluminium/all aluminium
(iii) Manufacturing	Internal recycling degree	Internal recycled waste (e.g., remelting)/all aluminium waste
	Applied internal repair strategies	Defect parts repaired/waste parts
(iv) Distribution and usage	Applied rethinking strategies	Product lifetime/average aluminium product lifetime
(v) Collection, sorting and transport.	Applied reusing strategies	Reused products/end of life products
	Applied repaired strategies	Repaired products/end of life products
	Applied refurbishment strategies	Refurbished products/end of life products
	Applied repurposing strategies	Repurposed products/end of life products
	Applied remanufacturing strategies	Remanufactured products/end of life products
	Circularity degree	(Reuse, repair, repurposed, remanufactured, and recycling streams)/landfill and incineration streams
	Quality of the waste stream	Proportion of homogenous and mixed waste stream (best to worst option)
	Closed loop	Homogenous and mixed waste stream/all waste streams

aluminium alloys. Notably, the manufacturer exclusively sources aluminium materials from the aluminium producer and its affiliated distributors, with no other external suppliers involved.

Furthermore, the entity responsible for collecting and sorting aluminium waste is engaged in the sale of mixed materials to aluminium producers. By mapping their current operational pathways and identifying underutilized routes, opportunities arise to explore alternatives for enhancing circularity. Collaborative efforts during the design phase empower these stakeholders to make informed decisions regarding alternative alloys. Recognizing that a change in alloy composition can enable enhanced recyclability, these changes can be applied across various aluminium alloy families.

To further boost return flows to the manufacturer, a shift in the business model is deemed necessary. The introduction of buy and return options, coupled with a transition towards servitization, is proposed as an effective means to increase the return of materials to the company. Subsequently, measures aimed at reusing components or subjecting them to melting and processing for new product creation have become imperative. Moreover, within this network, components and parts with substantial volume are identified for the establishment of homogeneous waste streams. The entity responsible for collection can then choose to resell these materials directly to manufacturers or to aluminium producers.

All three participating actors recognize the necessity of expanding their network by seeking additional partners willing to collaborate on circularity initiatives. As part of their strategic plan, they intend to establish a distribution network that facilitates the return of products and ensures homogeneous waste streams, directly benefiting manufacturing companies.

Enablers and barriers for establishing a robust circular value chain in the industry

In the pursuit of establishing a robust circular supply chain for aluminium alloying, workshops have uncovered various barriers and enablers for circular supply chains. These obstacles encompass aspects ranging from the initial supply of secondary raw materials to their final collection and sorting. Below, we summarize the main challenges hindering and the factors enabling the smooth transition to circular practices in the aluminium industry after applying a circular assessment method.

Barriers

- *Insufficient and unpredictable secondary raw materials*: The scarcity and uncertain timing of secondary raw materials create industry uncertainty.
- *Resistance to circular practices:* The aluminium industry is hesitant to embrace circularity beyond recycling.

- *Stringent quality requirements:* Particularly in the automotive and aerospace sectors, strict quality standards add complexity.
- *Acceptance of recycled materials and new aluminium alloys*: Resistance to accepting recycled materials in certain technical standards, coupled with concerns about heterogeneous quality and assurance, amplifies challenges.
- *Maintaining quality tolerances:* Ensuring quality tolerances for aluminium alloys using secondary materials is a delicate task.
- *Limited knowledge of alternative alloys:* There is limited knowledge about alternative aluminium alloys that can replace fewer circular ones.
- *Inexperience in circular design:* The industry lacks experience in designing products with circularity in mind.
- *Manufacturing challenges:* Low knowledge levels regarding high quality production using circular aluminium alloys and ongoing issues with defects.
- *Limited experience in de- and re-manufacturing:* Experience in de- and re-manufacturing parts and products is lacking, hindering circularity.
- *Financial challenges in distribution and usage:* High costs associated with aftermarkets for low-value products discourage circular practices.
- *Collection and sorting expenses:* High costs for detection, classification, and grading technologies for aluminium waste and determining circularity potential add financial burdens.

Enablers

- *Quality documentation:* Providing quality documentation for high quality aluminium alloys with secondary materials ensures reliability.
- *Quality tolerance parameters:* Identifying parameters for quality tolerances when using recycled aluminium alloys helps maintain consistent quality.
- *Eco and circular design:* Incorporating eco and circular design principles, along with knowledge of recyclable materials, fosters circularity.
- *Collaboration between producers and manufacturers:* Close collaboration between primary and secondary aluminium producers and manufacturers prepare components and products for circularity.
- *Digital technologies in manufacturing:* Integration of sensors and data management systems helps detect defects early, improving circular manufacturing.
- *Decision support systems:* Digital technologies, like decision support systems, enhance intralogistics and material flow management. Reducing collection and transportation costs and increasing digitalization of product and component information enhance circularity in collection and sorting processes.
- *Digital platforms for aftermarkets:* Digital platforms for aftermarkets extend product lifetimes through reuse and refurbishment.

- *Condition-based maintenance:* Implementing condition-based and predictive maintenance strategies prolongs product life.
- *Lifecycle tracking and tracing:* IoT sensors and historical data facilitate the tracking and tracing of lifecycle information for optimizing distribution and usage.
- *Automation technologies in collection and sorting:* Automation technologies aid in sorting waste materials and creating homogeneous waste streams.
- *Service providers and networks:* The formation of service providers and networks for managing homogeneous waste streams is crucial.
- *Data-driven decision-making*: Technologies supporting data-driven decision-making processes and trading platforms play a pivotal role in identifying circularity potential.

Discussion

Poor circular business model design and low market incentives are two main challenges in moving towards adopting different R-strategies to extend the lifetime of products and components. This study shows that aluminium recycling value chains are well established. However, determining optimal strategies, such as reuse (R3) and remanufacturing (R6), requires value stream analysis. A lack of decision-support methods can hamper practitioners' efforts to improve their circularity. The proposed framework, assessment criteria, and metrics aim to fill this gap and help practitioners understand the degree of circularity in their value chains. Unlike LCA, which focuses primarily on quantifying the environmental impact of a product and its value chain, this assessment method identifies the degree of circular pathways. This assessment method can be extended and combined with LCA to ensure the selected R strategies also result in positive environmental sustainability. One limitation is that practitioners may not have complete information on all stages of their value streams. Remine (R10), the valuable resources stored in old landfills and other waste plants, can also be considered and adopted by industries [39].

Circular initiatives in the aluminium industry also aim to create sustainable and environmentally responsible practices. Their primary focus is on developing efficient closed-loop systems that minimize the downcycling of aluminium, ensuring that it retains its value and quality properties throughout its lifecycle. This is especially crucial due to the extensive variety of alloys and alloy elements within the aluminium family. The challenges associated with cross-contamination between different alloys and other metals like iron (Fe) and copper (Cu) underscore the importance of these initiatives. Such contamination can lead to reduced material quality and hinder recycling efforts. By addressing these issues, circular initiatives contribute to resource conservation, reduced waste generation, and the overall sustainability of the aluminium industry. This not only benefits the environment but also supports economic and industrial objectives by maintaining the value of aluminium materials.

Therefore, efforts are aimed at developing more collaborative circular networks to increase upcycling, extend product lifetimes, and enhance value streams. Ultimately, this will reduce the need for new material extraction and landfill waste. While closed-loop recycling of aluminium cans is one of the most successful and established examples, not all parts of the cans are included in the closed loop. According to Niero and Olsen [20], there is room for improvement in this area. Conversely, many aluminium value chains utilize closed-loop recycling systems that incorporate waste from open loops, leading to the downcycling of materials. The main challenge in establishing closed-loop recycling and reducing downcycling lies in the collection, sorting, and refining stages of aluminium waste into high-value alloys [40]. High costs and poor network design are two other factors in making the reverse logistics of aluminium challenging [41]. Only a few industries, such as the automobile, have managed to optimize the logistics network, cradle to cradle, to recover metals and tyres to reduce the environmental impact [42].

Technology advances have improved the sorting and identification of aluminium waste, but there are still many other challenges to overcome. For example, automated physical separation and colour sorting technologies have improved aluminium sorting, even identifying the main aluminium alloy families [43]. However, surface roughness resulting from use and the effect of heat treatments during manufacturing can greatly impact the resulting colour of the scraps and therefore mislead identification and separation [44]. Laser-induced breakdown spectroscopy can be applied to a wide range of shredded scrap streams, but even when the scrap is clear, oxide formation on the surface could cause erroneous readings [45]. To refine waste aluminium, recent studies introduce methods to improve the chemical thermodynamic analysis by simulating smelting processes, indicating which elements can be removed and how far impurities can be controlled during the recycling of aluminium [46, 47]. However, the high variety of waste limits the effectiveness of the refinement process.

Track and trace technologies for life cycle information for aluminium value chains are strong enablers to help practitioners obtain more complete information. Information such as quality of aluminium production date, usage time, and environmental impact at different stages of the life cycle can improve the decision-making process, particularly in the "Collection, sorting and transport" stage (v). For example, material documentation such as the quality and types of used aluminium materials can have an impact on the final decision and enhance circularity by increasing the uptake of used aluminium. One main challenge is to obtain quality information throughout the complex value chain. Stakeholders in the aluminium industry are often scattered globally, which can potentially result in fragmented and unavailable information. Thus, newer digital tools such as digital product passports and blockchain could help to secure and facilitate better information sharing among the stakeholders within a complex supply chain to increase confidence in the use of used materials [48].

Conclusion and future work

Aluminium has great potential in moving towards circularity, and the common approach is recycling. Circularity assessment is important to help industry see the benefits of moving towards CE. Most of the assessment methods, including LCA, did not represent the collaborative nature of multi-stakeholders in the entire value chain of an industry. Therefore, in our work, we shift the attention of CE based on the characteristics of the aluminium industry and design a novel circular manufacturing assessment method for the aluminium industry. The novel circular manufacturing assessment method can help the aluminium industry prioritize different R-strategies such as remanufacturing (R6), repurposing (R7), refurbishment (R5), repairing (R4), and reusing (R3).

One limitation of this assessment method is that it does not account for by-products such as critical metals from aluminium product manufacturing or waste streams from other materials in the circular system. To recover critical metals from existing aluminium recycling processes, targeted recycling activities for aluminium products containing these materials are necessary. The assessment method is not addressing the changes in implementing different R-strategies, which can alter the supply and demand for secondary raw materials like aluminium alloys and the efficiency of scrap collection. Additionally, the boundaries of the aluminium value chains are regional, national, or international, and changes to these with increased recycling capacity in specific locations might alter the secondary raw material availability for the industry actors. Hence, future research should focus on integrating these material streams for successful closed-loop recycling.

Further research is needed to understand how the industry adapts to these future changes in material and quality flow. The system boundaries in the existing literature vary from national to global levels, with a focus on developed countries or China, but with limited information from other regions, despite the potential gains in developing countries. The assessment method also has limited consideration for recovering aluminium from hibernating stocks such as tailings and landfills. Large amounts of aluminium, including aluminium beverage cans, are being put in landfills worldwide, and recovery from these sources could be a potential future source for aluminium. However, the aluminium in landfills is not tracked and characterized, so information on the alloy and product class must be obtained upon recovery. Lastly, we acknowledge there is a possibility of overlooking relevant studies due to the use of terms and filters. We tried to include as many relevant studies as possible to develop this assessment method that can help practitioners evaluate and enhance the circularity of their aluminium materials and products.

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Appendix

Table 2A.1 Summary of the collected publications

Authors	*Type aluminium*	*Key points*
Charpentier Poncelet et al. [17]	Metal groups	Since the dissipation of metals has a negative impact on the environment and the dissipation flow becomes inaccessible for future users, the authors propose two LCIA methods for capturing the expected dissipation patterns of metals after extraction.
Albuquerque et al. [18]	Packaging	Combined LCC and externalities CE to analyse the benefits of using aluminium packing in food. The results indicate an economic benefit and CO_2 reduction.
Fellner et al. [19]	Municipal Solid Waste	Conduct MFA to analyse the current flows of secondary resources for selected commodities in the EU and to predict their future quantities in the case that the Circular Economy Package The results of the investigations indicate that today, about 36% of the EU's production of aluminium is made out of secondary raw materials, which is significantly lower than iron & steel and paper & board (50%).
Niero and Olsen [20]	Cans	LCAs of aluminium products have typically been based on pure aluminium (neglecting the presence of alloys) and can be oversimplified. LCA revealed that the close product loop option has a lower climate change impact over the other 30 recycling scenarios.
Sevigné-Itoiz et al. [21]	Aluminium scrap	Integrate MFA and CLCA for evaluating aluminium flows and estimating GHG emissions within a market context. GHG results show that the increase in old scrap exports avoids more GHG emissions than if the old scrap is recycled locally, providing up to 250% more in GHG savings.
Haupt et al. [22]	different types of material waste	Conduct MFA on the recycling of aluminium and other waste from municipal solid waste (MWS) in Switzerland. Aluminium postconsumer scrap is mostly used for castings in automotive applications. Therefore, its recycling occurs mostly in an open-loop fashion.
Low et al. [23]	Flat panel display monitor	Simulate the carbon footprint of a closed-loop production system using the PSILA-CFP model. A significant contributor to CFP reduction is the closed-loop material recycling of aluminium, which accounts for 8.13 million kg of CO2e, or 20.37% of the total CFP reduction.

(*Continued*)

Table 2A.1 (Continued)

Authors	*Type aluminium*	*Key points*
Stotz et al. [24]	Cans	In most cases, metals are recycled in an open/cascade recycling loop, where dilution and quality losses occur. Perform the LCA of an aluminium beverage can (ABC) in seven scenarios. The production of ABC and primary aluminium contributes the most to GWP.
Nishijima et al. [25]	Air conditioners	Formulate a dynamic discrete choice model for ACs in Japan to quantitatively analyse the relationship between rising product prices and consumer replacement choices. The result shows that a 30% price increase can reduce both metal consumption and GHG emissions. The authors suggest that consumers will use products longer so long as the value of the product's enhanced durability and longevity matches the increased price of the product.
Moraga et al. [26]	Laptop	Study scenarios with different CE strategies (energy recovery, recycling, refurbishing, and reuse) using LCA. Scenarios with cycles of refurbishment and reuse showed improved resource efficiency compared to recycling scenarios. The energy recovery improvement was up to 189% (refurbishment) and 157% (reuse) in the case of aluminium.
Ghisellini et al. [27]	Construction and demolition waste	Perform a LCA study to evaluate the energy savings from the implementation of recycling scenarios in the construction sector in Italy. The results show the recycling option for the C&DW is better than landfilling. The non-hazardous C&DW fractions into aggregates of different types and secondary materials (iron, steel, and aluminium) have the potential to reduce the dependence of the sector on fossil energy and associated environmental impacts.
Czerwinski [28]	Car parts	The light weighting strategy is growing as a part of the CE and is the solution for both modern mobility and transportation; its objectives are not exclusively focused on the reduction of weight but also cover other aspects such as structural efficiency as well as economic and environmental impacts.

(*Continued*)

Table 2A.1 (Continued)

Authors	*Type aluminium*	*Key points*
De Meester et al. [29]	Waste Electrical and Electronic Equipment (WEEE)	Combine material flow analysis (MFA) and life cycle assessment (LCA) to optimize the environmental performance of the WEEE recycling chain. Aluminium achieves the highest high-end material recoveries of 46%. Reuse and better source separation can help reduce the uptake of natural resources.
Díaz-Ramírez et al. [30]	Batteries	Perform cradle-to-gate LCA analysis on two battery study cases: lithium manganese oxide and vanadium redox flow (VRFB) batteries. The study revealed the need to consider material recyclability, such as aluminium, for promoting circularity and battery eco-design. The main results confirmed that the use of recycled materials provoked a descent in all environmental indicators associated with both battery types, especially in terms of toxicity and ecotoxicity for VRFB.
Morgan et al. [31]	Beer	Conduct an LCA of seven micro-breweries with three mitigation options (e.g. aluminium cans). All participating breweries can achieve reductions across multiple impact categories if single-use glass bottles are changed to aluminium cans or reusable glass, and further reductions are possible if the mode of transport is changed from small delivery vans to lorries for distribution to retailers.
Hertwich et al. [32]	Buildings and vehicles	Reviewed emissions reductions from material efficiency (ME) strategies applied to buildings, cars, and electronics. There can be a systematic trade-off between material use in production and energy use in operation. The largest potential emission reductions quantified in the literature result from more intensive use of and lifetime extension for buildings and the light-weighting and reduced size of vehicles.
Niero et al. [33]	Cans	Perform an LCA of an aluminium can system representing different levels of the Cradle-to-Cradle certification criterion, considering different strategies to achieve 100% RE in the manufacturing stage. The results show that for product systems where most of the environmental impacts come from raw material extraction and production, the RE share in the upstream processes needs to be considered.

(*Continued*)

Table 2A.1 (Continued)

Authors	*Type aluminium*	*Key points*
Zink et al. [34]	Various types of aluminium	Develop the aluminium market model to estimate aluminium displacement is to estimate these response parameters. Sensitivity analyses reveal that displacement estimates are sensitive to uncertainty in price elasticities. Results suggest that 100% displacement is unlikely immediately following a sustained supply-driven increase in aluminium recycling and even less likely in the long term. However, zero and even negative displacement are possible.
Wang et al. [35]	Lithium batteries	Conduct a cradle to gate LCA to analyse and compare the environmental impact of lead acid battery (LAB), lithium manganese battery (LMB) and lithium iron phosphate battery (LIPB). Aluminium shell is the key material of LMB, improving the utilization efficiency of refined lead, tin, lithium manganese oxide, lithium iron phosphate, and aluminium shell in the battery production process has an obvious effect on reducing the environmental impact of the battery production process.
Niero et al. [36]	Cans	A framework combining LCA and the Cradle to Cradle® (C2C) certification programme for the development of continuous loop packaging systems, which was conceived for aluminium cans in the context of the Carlsberg Circular Community.

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Chapter 3

Framework for life cycle assessment-based circular business model development

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Introduction

The role of the manufacturer in progressing towards sustainable development is expressed in sustainable development goal (SDG) No. 12 of the United Nations as to "ensure sustainable consumption and production patterns" [1]. Today, there has been a significant negative environmental impact on a global scale, with unsustainable resource use [2], climate change [3] and the deterioration of biodiversity and ecosystems [2]. The circular economy (CE) is a concept that offers a path for achieving SDG No. 12 by decoupling economic growth from environmental degradation [4].

CE research has progressed from purely conceptual work towards implementation support [5]. Consequently, circular business models (CBMs) have gained momentum as a way of focusing CE efforts [6–9]. Despite the conceptual link between SDG No. 12 and CE, all CE efforts must still be evaluated to safeguard their contribution to sustainability [10]. Frishammar and Parida [6] describe CBM development as an iterative process, while [11] points to the role of learning and experimentation in CBM development. Some authors [12, 13] recommend using assessments in the early stages of CBM development so that the impacts of different strategies are clear from the first stages of innovation processes. Haupt and Zschokke [14] and Peña et al. [15] further suggest that life cycle assessment (LCA), an analytical tool for the evaluation of environmental impacts associated with a product or a service [16], is well suited to evaluate the environmental sustainability of CE efforts. However, to contribute to systematic change, LCA must also be integrated as part of a decision-support system. This can be done at the conceptual level through life cycle thinking (LCT), in the management system through life cycle management (LCM), in product development through eco design, in the value chain through supply chain management (SCM) or as a part of the business model (BM) itself.

Despite the evolving recent literature debating assessment methods for measuring the environmental effects of CE and CBMs [17–19], there is a need for greater knowledge on how LCA is applied for this purpose. Further, how

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can LCA be applied, not only for evaluation but also as a starting point for developing CBMs? Through a systematic literature review, this chapter aims to explore what current research tells us about how LCA can and should be used for CBM development. Three research questions were applied to guide the work: (1) to what type of CBM innovation is LCA applied? (2) In what way is LCA performed? (3) How is LCA used to support decision-making in CBM development? Based on the findings, we propose a framework for applying LCA in CBM development to gain a competitive advantage.

The chapter is structured as follows: The theoretical background on CE, CBMs and LCA for CBM development is presented in Section "Theoretical background". The research design is introduced in Section "Research design", followed by the findings and discussion in Section "Findings and discussion". Last, Section "Conclusions" provides conclusions and recommendations.

Theoretical background

Circular economy and circular business models

CE as a concept originated within business and policy organisations, such as the Ellen McArthur Foundation, which defines CE as "an industrial economy that is restorative by intention and design" [20, p. 14]. However, the idea of a restorative economy can be traced back to the industrial ecology principle of "closing loops" [21] or even to [22] the "spaceman economy", where throughput is minimised and maintaining stocks is the main goal [23].

Kirchherr et al. [24] introduce reducing, reusing, recycling and recovering materials (the 4 Rs) as strategies to progress towards a CE. Reike et al. [25] expand on this, proposing 10 R strategies, grouped into three groups of circular strategies: (1) downcycling (remine, recover, recycle and repurpose), (2) product upgrade (remanufacture, refurbish and repair) and (3) users' choices (reuse, reduce and refuse). For businesses, CE strategies involving different Rs can help direct efforts to become more circular and sustainable in their operations. But to be successful in transforming towards CE, the efforts must be harmonised with the company's BM. A BM "describes the rationale of how an organization creates, delivers, and captures value" [26, p. 14]. Considering the definition of a CE [20], a CBM thus aims to create, deliver and capture value in a manner that ensures a restorative economy with closed resource loops by employing one or several circular strategies (Rs). Bocken et al. [27] present six BM strategies for slowing and closing loops: (1) an access and performance model with user needs as the point of departure (i.e., no physical products); (2) the remaining value of the product after a use cycle is utilised to extend the product value; (3) a classic long-life model where design for longevity and repair is central; (4) encouraging sufficiency, where solutions to reduce end user consumption are essential; (5) extending resource value; and (6) industrial symbiosis. These strategies represent pathways towards circularity and can be followed individually or in combination with a CBM. This chapter builds upon both [27] and [25] when analysing the circular strategies presented in the articles.

New BMs can be introduced in several ways, depending on the organisation. Geissdoerfer et al. [28] describe different types of CBM innovation: (1) transformation (changing from a traditional BM to a CBM); (2) circular start-ups (creating a CBM from scratch with no existing BM); (3) diversification (keeping the current BM and creating an additional CBM); and (4) acquisition (acquiring an existing CBM and integrating it into the organisation). The circular strategy scanner proposed by [12] can support circular innovation processes in manufacturing companies by providing a structured approach for mapping, investigating and finding new opportunities for circularity. However, further work focusing on linking assessments of economic, environmental and social impacts to the framework is still needed [12].

Assessing the environmental impacts of CBMs

Although the CE concept represents a fruitful path for sustainable development, the link between CE and sustainability is not certain in all situations [5, 10]. CE assessment methodologies are important for measuring the effects of CE efforts and ensuring their link with sustainable development. Methodologies to evaluate CE come in two categories: (1) specific CE performance measures and (2) established assessment methodologies such as material flow analysis (MFA), input output analysis (IA) and LCA that quantify the environmental impacts of CE systems.

LCA is the most frequently used method for CE performance assessment [19], and it is also suitable for evaluating the environmental sustainability of circular systems [14, 15]. LCA can be divided into four main stages: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation [29]. LCA is typically used for purposes such as product improvement and development, decision-making support, strategic planning, marketing, ecolabelling and policy development. Multiple methodological variants of LCA exist [30], but the two main types are attributional LCA, based on average production data in the value chain, and consequential LCA, based on marginal changes in the market [31]. Despite the broad use of LCA, the methodology has limitations, including the availability of data, its exclusive focus on the environmental dimension of sustainability, and being based on linear modelling [32]. Efforts to offset these limitations have been made over the years, but methodological challenges still exist, and some of these limitations are prominent when applying LCA to new circular systems [33–35] and evaluating scale-up potential [36–38]. CBM development involves rethinking the whole production, use and disposal dimensions associated with products (and services). Applying LCA to circular strategies to support decision-making often means evaluating future impacts. For this purpose, future-oriented prospective LCA methodologies have evolved to offset the limitations of the traditional method on future systems [31].

Transforming towards CBM is a process [6], and the most valuable location of LCA within the process has been greatly discussed [27, 39]. Jørgensen and Remmen [13] suggest using assessments as a point of departure for circular strategies. This chapter will explore what the existing scientific literature tells us on whether LCA is a suitable method to direct CBM development and how it can best be applied.

Research design

Systematic literature review

To explore how LCA can and should be used for CBM development, this chapter uses a systematic literature review. A systematic literature review is a suitable method to investigate the existing evidence within a research field and identify gaps in the current knowledge that require further exploration [40]. Thus, to be able to provide recommendations on the use of LCA for CBM development, we applied a systematic approach, starting by defining the goal and research questions, followed by data collection, sorting and analysis, each of which is described in further detail below.

Data collection

Initial exploration of the literature quickly revealed that the amount of literature on LCA and CE is vast to an extent that is not suitable for an in-depth review. However, through random sampling, it became apparent that most literature on LCA and CE does not provide insights into how LCA can be used, but rather mentions it in a broader CE context. Aware of the risk of excluding relevant literature, this chapter focuses solely on research explicitly using the term "circular business model". This decision is grounded in the goal of investigating how LCA is used in CBM development. The Scopus database was used to perform the search, and the search string used was *TITLE-ABS-KEY (("circular business model" OR "circular strategy") AND ("life cycle assessment" OR "life cycle analysis"))*. Scopus was chosen because it provides a comprehensive and curated overview of scholarly literature. Combined with snowballing, this provides an appropriate overview of the scientific literature.

"Circular strategy" is included because it is viewed as a central part of a CBM, and BM innovation can involve exploring different circular strategies. "Life cycle assessment" and "life cycle analysis" are both included as they are commonly used terms with the same meaning. To reduce noise and the amount of literature to process, the search is performed on titles, abstracts, and keywords. Articles not including the search words in any of these components are considered out of scope for this work. The time interval is set to 2012–2022, and only literature in English is included. The initial assumption is that the

Table 3.1 Overview of the paper screening procedure leading to the final sample selection

Date performed: 10.1.2023			
Process step	*Publications (#)*		*Removed/added*
Year: 2012–2022			
Language: English			
Document type (peer-reviewed): article, review, conference paper, book chapter, conference review	62		
Title screening	21 (green)	33 (yellow)	8 (red)
Abstract screening	14		−7
Snowballing	19		+5

Table 3.2 Inclusion/exclusion criteria used for article screening

Inclusion criteria	*Exclusion criteria*
Article describes a performed LCA.	Article does not describe a performed LCA.
Article directly or indirectly describes the use of LCA results for decision making for circular strategies or CBM.	Article does not describe the use of LCA results for decision-making for circular strategies or CBM.

majority of relevant literature has been published in the last five years, so a ten-year time interval is set to also include earlier research. The findings support the selection of intervals, with the oldest article included being from 2016. Peer-reviewed literature is a criterion to ensure the quality of findings and provide clarity as to the motivations and biases of the performers in LCA. After filtering for these criteria, the number of articles returned is 62, as shown in Table 3.1. Applying the inclusion/exclusion criteria, presented in Table 3.2, the 62 articles are screened by title. This is done by sorting them into categories of green, yellow and red, where green means within scope, yellow means unclear and red means out of scope. The categories of green and yellow articles are then screened on abstract, further reducing the number of articles. The references in the articles are subsequently analysed to identify additional articles to review (snowballing). The final number of papers for assessment is 19.

Guidelines for analysis

Three research questions provide the foundation for the analysis:

1 To what type of CBM innovation is LCA applied?
2 In what way is LCA performed?
3 How is LCA used to support decision-making in CBM development?

Table 3.3 Guide for analysis of selected literature

RQ	*Questions*	*Explanation*
1	What type of BM innovation is applied?	Types of CBM innovation [28]: (1) transformation (2) circular start-ups (3) diversification (4) acquisition
	Which circular strategies are presented?	How is the suggested strategy contributing to reducing resource consumption? (R-strategies) [25, 27]
2	Scope and system boundaries	Cradle to gate/grave/cradle?
	Type of LCA	Future-oriented or prospective LCA Multiple cycles (use/material) (allocation) Impact categories? Scenarios?
	Functional unit	What is measured?
3	What findings from LCA are used, and how?	Is LCA used to forecast potential environmental impacts? Micro (company), meso (industry) or macro (society)-level decision support [31]
	Drivers and barriers for applying LCA	Barriers or challenges for LCA in a circular system?

Each paper is analysed and thematically synthesised [40] using the analysis guide shown in Table 3.3.

Findings and discussion

This section describes the key findings as to how LCA can and should be used for CBM development, taken from the 19 articles analysed. Table 3.4 summarises the key findings for all articles analysed, and the research questions are addressed in Sections "What type of business models is LCA applied to?" "What type of LCA is performed?" and "LCA as decision-making support for CBMs".

What type of business model is LCA applied to?

This section aims to shed light on the types of BMs assessed using LCA, which R strategies are explored and compared, and how the circular value proposition is described within the literature. Of the analysed articles, none explicitly addressed the type of BM development described by [28]. When addressed implicitly, LCA is used in the context of existing businesses transforming into or adding (i.e., diversification) a CBM. The lack of representation of start-ups within the literature might indicate that they give measuring

Table 3.4 Overview of the key findings for the 19 articles analysed

Title	*Authors*	*Product*	*Circular strategies*	*System boundaries*	*Impact categories*	*LCA Scenarios*	*Decision support*
Evaluating the environmental performance of a product/service-system business model (BM) for Merino Wool Next-to-Skin Garments: The case of Armadillo Merino®	Bech et al. [41]	Wool garments	Product-service systems (PSS)	Cradle to cradle	Climate change	2, Reference system and PSS	Micro
Intermediate bulk containers re-use in the circular economy: an LCA evaluation	Biganzoli et al. [42]	Intermediate bulk containers	Reuse	Cradle to grave	Multiple	Reference system vs.reconditioning	Micro
Life cycle assessment (LCA) to ensure the sustainability of circular business models (CBMs) in manufacturing	Bjørnbet and Vildåsen [43]	Gas Containers	Recycling lifetime extension	Cradle to grave	Not given	Not given	Micro
Developing CBMs: LCA and strategic choice	Ellingsen and Vildåsen [44]	Beds	Not given	Cradle to grave	Multiple	None	Micro
Combining eco design and LCA as decision-making process to prevent plastics in packaging applications	Foschi et al. [45]	Plastic food containers	Recycling	Cradle to grave	Multiple	None	Micro

(*Continued*)

Table 3.4 (Continued)

Title	*Authors*	*Product*	*Circular strategies*	*System boundaries*	*Impact categories*	*LCA Scenarios*	*Decision support*
The paradigms of Industry 4.0 and circular economy (CE) as enabling drivers for the competitiveness of businesses and territories: The case of an Italian ceramic tile manufacturing company	Garcia-Muiña et al. [46]	Ceramic tiles	Not given	Cradle to gate	Multiple	None	Micro
LCA of innovative CBMs for modern cloth diapers	Hoffmann et al. [47]	Diapers	Re-use/PSS	Cradle to grave	Multiple	4, Reference system, reuse, and 2 PSS	Micro (macro)
Is prolonging the lifetime of passive durable products a low-hanging fruit of a CE? A multiple case study	Kaddoura et al. [48]	Passive durable products (5 cases)	Lifetime extension/ PSS	Cradle to grave	Multiple	2, Reference system and PSS	Micro
To rent or not to rent: a question of circular prams from a life cycle perspective	Kerdlap et al. [49]	Prams	Re-use, lifetime extension/PSS	Cradle to grave	Multiple	4, Reference system, rental and 2 reuse	Micro (macro)
Using a LCA to identify the risk of “circular washing” in the leather industry	Marrucci et al. [50]	Leather	Internal reuse/ recycling	Cradle to gate	Multiple	2, Baseline and circular	Micro
Circular building materials: carbon saving potential and the role of BM innovation and public policy	Nußholz et al. [35]	Building materials	Material reuse	Cradle to grave	Climate change	None	Micro, meso

Material reuse in buildings: implications of a CBM for sustainable value creation	Nußholz et al. [51]	Building products	Material reuse	Cradle to gate	Climate change	2 for each material, reference system and circular	Micro, meso
A greenhouse that reduces greenhouse effect: how to create a circular activity with construction waste?	Romnée et al. [52]	Greenhouse	Repair, reuse	Cradle to grave (excluding end of life)	Environmental impact indicator: ReCiPe Endpoint (H)	5, 4 circular and reference system	Micro
Two LCA-based methods to analyse and design complex (regional) CE systems. Case: making water tourism more sustainable	Scheepens et al. [53]	Water tourism	PSS	Cradle to gate	Climate change	None	Micro, meso and macro
Integration of energy flow modelling in the LCA of electric vehicle battery repurposing: evaluation of multiuse cases and comparison of CBMs	Schulz-Mönninghoff et al. [54]	Electric vehicle batteries	Reuse, repurposing, remanufacturing and recycling	Cradle to grave	Climate change and resource depletion	2, Energy consumer perspective and automotive perspective	Micro, meso, macro
Integrating LCA and blockchain technology to promote circular fashion—a case study of leather handbags	Shou and Domenech [55]	Leather bags	Re-use, exploring circular materials options	Cradle to grave	Multiple	3, Reference system, reuse and material substitution	Micro

(*Continued*)

Table 3.4 (Continued)

Title	*Authors*	*Product*	*Circular strategies*	*System boundaries*	*Impact categories*	*LCA Scenarios*	*Decision support*
The environmental and material implications of circular transitions—a diffusion and product life cycle based modelling framework	Sigüenza, et al. [56]	N/A	Not given	Cradle to grave	Climate change	None	Macro
CBMs of washing machines in the Netherlands: material and climate change implications towards 2050	Sigüenza et al. [57]	Washing machine	Product lease and pay-per-use	Cradle to grave	Climate change	None	Macro
LCA framework to evaluate CE strategies in existing buildings	Zimmermann et al. [58]	Buildings	Lifetime extension, repair	Cradle to grave	Climate change	3, Reference system, preservation and renovation	Micro

the impacts of circular strategies lower priority than larger companies [59], that they have fewer resources available to be involved in research, or that they simply experience more barriers when conducting LCAs [31]. The ability of this analysis to provide recommendations for more radical CBM development is limited by the lack of start-ups and radical CBM development processes.

Of the analysed articles, the majority (16) described the circular strategy (i.e., R strategy) explored. Those that did not were articles describing frameworks or methodological development [46, 56] or describing a more open-ended exploration of CBM development [44]. Variations of PSS were discussed by several authors [47, 49], as were lifetime extension/repair, recycling and the use of secondary materials.

What type of LCA is performed?

Most articles performed LCA from cradle to grave, including raw material extraction, production, use and end of life. Others applied cradle to gate system boundaries, excluding the use and end-of-life stages [46, 50]. Most articles performed full LCA. Some [47] performed screening LCA, i.e., a basic overview of the major impacts in a product life cycle. Das et al. [59] performed a survey in which the majority of participants reported that environmental impacts are measured for the current BM but that future impacts from new circular routes are not measured. This is confirmed by our research; none of the articles mentioned prospective or future-oriented LCA explicitly. Sigüenza et al. [56] proposed a mixed-method diffusion and product life cycle-based modelling framework, aiming to evaluate the effects of the circular transition in line with prospective LCA approaches.

Of the analysed articles, seven only quantified the environmental impact as it relates to climate change (typically measured in kg CO_2-eq.) and did not explore the potential problem shifting of the proposed circular strategies. While some performed LCA as a starting point (baseline) for CBM development on the current BM, most also provided scenarios for the development of the proposed circular strategies.

An in-depth analysis of the LCA methodologies that have been applied in the articles is not possible, as the level of detail reported is not sufficient to provide a deeper understanding of the methodology used. The standards that have been followed and which impact assessment methods have been used are rarely specified.

LCA as decision-making support for CBMs

LCA can be used for decision-making support in three ways: micro-level decisions, meso/macro-level decisions and accounting [31]. Microlevel support implies that the decision support of the LCA will not lead to large system changes; meso/macro level decision-making support is where results support decisions leading to larger structural changes (e.g., at the industry or policy levels); and the last is where the purpose is purely descriptive, such as for reporting purposes. Most of the studies described LCA that was applied on a micro level, where the LCA provided results to support decision-making on a product or business level. Sigüenza et al. [56] developed a framework to support macro-level decisions and applied it to washing machines in the Netherlands. Nußholz et al. [35] provided specific examples of how policies can help remove barriers through incentivising waste collection and the recovery market.

When evaluating circular scenarios (e.g., reuse and rental models), product lifetime is crucial but also uncertain [49]. Bjørnbet and Vildåsen [43] pointed to the use stage and the end of life stage as those with the highest uncertainty in terms of data for LCA, yet they are also core life cycle stages in CBMs. This uncertainty can be addressed either within the LCA model (e.g., sensitivity analysis, scenario analysis) or in the decision-making process [60]. Data acquisition and increased uncertainty during experimentation are barriers that keep companies from measuring the environmental impacts of new circular strategies [59]. Obtaining data represented a major challenge for the two circular scenarios [55].

Framework for LCA-supported CBM development

Based on the reviewed literature, we propose a framework (Figure 3.1) that illustrates a suggested process as well as the associated pitfalls and recommendations for each step of CBM development. Variations of LCA exist to offset the methodological limitations (such as forecasting), but we find that they are seldom used. Therefore, we propose a generic framework to support the process, keeping an eye out for potential pitfalls. To enhance the power of LCA in supporting decisions in CBM development, the framework recommends using LCA both in the early and later stages of the process.

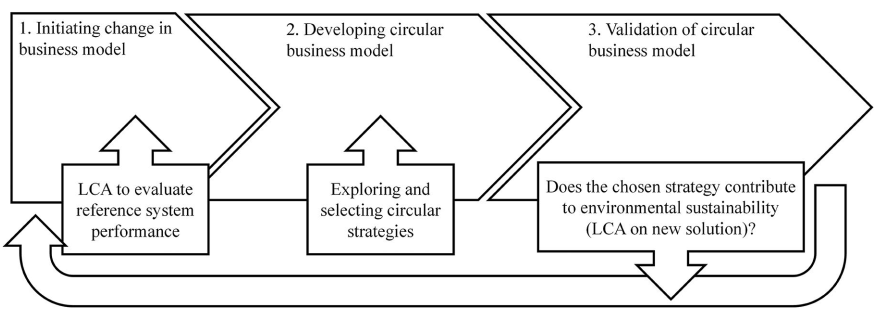

Figure 3.1 Generic framework to support iterative, LCA-based CBM development. Adapted from [6].

This utilises the strengths of LCA in gaining insight into the product lifecycle at an early stage [43], while at the same time reducing the risk of "circular washing"—a type of greenwashing where implementing circularity does not contribute to environmental sustainability [50].

The role of LCA in initiating change

Transformation opportunities should be explored in the early stages of CBM development [6]. Foschi et al. demonstrate how applying LCA in the early-stage design can support more sustainable options for food packaging [45]. LCA can facilitate communication with stakeholders and provide a common, fact based footing for discussion [43]. LCA provides a clear presentation of the environmental impact of the different materials used in products and thus incentivises the exploration of alternative materials [44].

A potential pitfall in this step is being restricted by the LCA. Quantifying results for the current product life cycle can lead to a strong focus on the existing product life cycle. LCA is well suited to addressing global and regional environmental challenges, but less suited to addressing environmental challenges where spatial resolution is of high importance, such as biodiversity loss.

The role of LCA in exploring circular strategies

The second stage in CBM transformation is designing and/or developing a CBM and exploring potential circular routes (R strategies) [6]. The strengths of LCA lie in revealing environmental hot spots and comparing the potential of different circular strategies to reduce impacts [55], making it suitable for exploring and selecting circular strategies. For product service systems (PSS), [41] suggested applying LCA in early stage development, pointing out that the functional unit must be set with caution if LCA is to provide a decision-making foundation for comparing PSS with other circular strategies. A challenge in this regard is that LCA on its own does not provide options for change, such as which materials can be substituted, which production processes can be improved/replaced, or how function and value can be redesigned. These options must be found outside of the LCA, after which the LCA can provide analytical support to evaluate the options for changing the BM.

The role of LCA in validation

Finally, the CBM must be validated and implemented. LCA can play a key role in this stage by ensuring the environmental sustainability of the proposed CBM. The existing literature underlines the importance of this step [50]. However, there are several barriers not addressed by LCA. Nußholz et al. [51] employed a multi method approach to investigate the implications for both the enterprise and other stakeholders in the value chain. Scheepens et al. [53] combined LCA with the value perspective to enhance decision-making support for CBM development. Consumer acceptance is also a crucial element to successful CBM implementation but was not thoroughly considered in the literature. Validation of the CBM should be accompanied by assessment methods for the implications of the proposed CBMs on the industrial (meso) and societal (macro) levels to uphold the systemic dimension of CE [54], as well as economic and social implications. As expressed by Romnée et al. [52], the LCA of the repair and reuse strategy does not take into consideration the social elements of the new BM, such as working conditions.

Conclusions

Applying LCA to CBM development

The purpose of this chapter is to shed light on how LCA is applied to CBM development through a systematic literature review, including an in-depth analysis of 19 articles. All the analysed articles applied (or described the application of) LCA for the exploration of circular strategies in CBM development. Despite the numerous variations of LCA that exist to offset potential methodological limitations (such as forecasting), we find that these more sophisticated methods are seldom used for real-life cases within the literature.

Several of the articles also reported environmental impacts within one category exclusively (i.e., climate change). This choice seems logical due to the severity of the climate change problem and the current considerable focus on resolving it. However, this limited focus fails to utilise one of the key strengths of LCA as decision-making support—the avoidance of circular routes where environmental improvements are offset due to problem shifting between environmental impact categories.

This chapter sets out to examine the current state of LCA in CBM development by performing a systematic literature review. The findings provide some implications for further development, but it is important to note that outcomes from published academic work and real-life experimentation might deviate [59]. A mixed-methods approach is required to assess circular strategies to offset the methodological limitations of LCA, such as forecasting, cover the broad systemic scope of CE (micro, meso and macro levels); and ensure economic, social and environmental sustainability. Future research should incorporate more holistic methods for decision making support to overcome this limitation.

Although the empirical base for evaluating CBMs through LCA is growing, there is still a challenge in connecting the associated impacts of CBMs on micro and macro levels [61]. From a company perspective, the macro considerations must be included in such a way that complexity and restrictions for use are not increased. Adding macro considerations will typically require that assessments for multiple system levels are done either in sequence or in parallel, with possible subsequent iterations between the assessments.

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Chapter 4

Environmental upgrading and bargaining power

A case study of Norwegian manufacturers

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Introduction

The orchestration of the global economy and economic activity is dominated by global value chains (GVCs; or global production networks) [1]. Since the late 1970s, this economic organization has created a division of labour with the primary objective of economic gains and maximum value capture within the lead firms (multinational companies) of global value chains [2–4]. With growing attention to climate change and the depletion of natural resources, researchers have increasingly become interested in studying the (often negative) impact of businesses and industries on the environment. Within the literature on global value chains (GVCs), this endeavour has been captured in the concept of environmental upgrading (EnvU) [5]. EnvU can relate to any change that results in a reduction in a firm's ecological footprint, thus including carbon footprint, biodiversity, and the exhaustion of natural resources [5]. This can be done related to both products and processes, but also in the way that the firm is organized and how products are handled at the end of life (i.e., when it's regarded as waste in the linear economy) [5, 6].

Firms' ambition to reduce their impact on the environment and policies that induce or force them to do so are necessary to achieve the 1.5 degree-target set by the UN by 2050. EnvU can be driven by different governance instruments and pressures that firms face. The potential of firms to conduct EnvU, of any form, is influenced by a range of factors related to these governance instruments [5], such as their capabilities to comply with the set requirements, to change design, or to innovate. The EnvU literature has pointed out that position in the global value chain can influence who bears the costs of EnvU, as lead firms can push the costs of EnvU onto their suppliers, implying that power can influence EnvU [7]. However, thus far, the literature on EnvU has not paid specific attention to the role of power in EnvU processes. The GVC literature has asserted that power and governance shape the configuration of and interaction between actors within value chains and that this power is not uniformly distributed among value chain actors [8–10]. Given this asymmetric distribution of power within value chains, we argue that the

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ability of actors within GVCs to conduct EnvU differs and is conditioned by power relations between value chain actors. Furthermore, we assert that there is a need to better understand how these power relations, and particularly that of bargaining power, influence the potential for suppliers in GVCs to conduct EnvU.

This chapter provides novel insights on the barriers to EnvU, with emphasis on how bargaining power – or rather, the lack thereof – within GVCs influences suppliers' potential for EnvU. The literature on EnvU has sketched out the different drivers of EnvU and the levels on which these can be found. While most GVC studies on EnvU have focused on lead firms, our emphasis on suppliers contributes to what has been described as the *embryonic* literature on EnvU focusing on supplier perspectives [11]. Particularly in this chapter, we focus on the role of bargaining power (i.e., 'the relative capacity of each of the parties to compel or secure agreement on its own terms' [12], as this form of power is especially important in the inter-firm relations that we focus on [13]. Our qualitative case study of 8 Norwegian manufacturers, who supply different global industries with components and products, is guided by the research question: *how does bargaining power within global value chains influence the ability of suppliers to conduct EnvU?*

In the following theory sections, we discuss EnvU in GVC and the GVC literature's conceptualizations of power and governance, focusing on bargaining power. Section "Methodology" presents our methodology and data sources, followed by a presentation and discussion of our empirical findings in Section "Environmental upgrading in Norwegian manufacturing". In Section "Conclusion", we conclude.

Environmental upgrading in global value chains

Literature on upgrading within GVCs has until recently been concerned with studying economic upgrading, i.e., how firms can increase their economic return and improve their positions in the respective value chains [14, 15]. Later, social upgrading, i.e., '…process of improvement in the rights and entitlements of workers as social actors, which enhances the quality of their employment' [16], also became a topic of interest in the GVC literature. More recently, the literature on GVC introduced the concept of EnvU to address the environmental aspect of modern economic activities [17]. The definition of EnvU has slightly changed over the years since it was introduced for the first time. In this chapter, we understand EnvU as 'any change that results in the reduction of the firm's ecological footprint - such as their impact on greenhouse gas emissions, on biodiversity losses and on natural resources overexploitation' [5]. Changes aimed at reducing the environmental impact of production systems and value chains can take place on the product, process, and organizational level [5], as well as end of life (i.e., the handling of products when they are discarded) [6]. De Marchi et al. [5] emphasize that these types or levels of EnvU can overlap, as one change can influence different levels. However, this differentiation or typology is necessary for practical and analytical reasons.

In addition to defining the types of EnvU, the literature has dedicated much attention to drivers for EnvU. EnvU can happen due to pressures external to firms, when states or non-firm organizations push firms to make changes. Lead firms can also drive EnvU by setting requirements for their suppliers, be it in form of compliance with specific standards or demanding changes in products. Internal firm motivations can also lead to EnvU. For example, firms can make changes to their processes to achieve cost savings or develop competitive advantages [5]. While previous literature has mostly focused on EnvU from lead firms' (and some studies focusing on first-tier suppliers) point of view, the newly suggested framework also aims at including other actors to analyse how they can influence EnvU [18].

The existing literature on EnvU has been expanding its geographical scope; however, it mostly focuses on the Global South with a few exceptions [17, 19–21]. As different countries have different mounting pressures from, e.g., the government, NGOs, and other non-economic actors to drive EnvU, we see it necessary to explore EnvU in other geographical contexts. In addition, GVCs and their EnvU can vary in different industrial sectors. The existing literature has, among other, covered apparel [11], agriculture [18], and maritime [19] value chains. However, we believe that this literature could still benefit from more studies on other industries, as well as studies on countries in the Global North. This chapter, with its empirical focus on the Norwegian manufacturing industry, contributes to this.

Independent of industrial sector or geographical location, the EnvU literature has identified the importance of innovation in EnvU processes [22] and how suppliers rely on innovation to perform EnvU in GVCs [21]. It has also explored how suppliers manage to conduct EnvU under multi-scalar environmental pressures [23]. Despite recent contributions improving our understanding of EnvU processes among suppliers, our understanding of how power and GVC governance influence suppliers' ability to conduct EnvU remains limited. Our emphasis on supplier–buyer relationships implies a firm-centric view in terms of EnvU, where we investigate how suppliers' potential to reduce their impact on the environment (through EnvU) is influenced by bargaining power.

Power in global value chains and production networks

The organization of the global economy into global value chains has resulted in dispersed power and chains of actors who are subject to power asymmetries. GVCs are controlled by lead firms (multinational companies) that, to a greater or lesser degree, have power over the different tiers of suppliers (Tiers 1–2–3) in the value chain. This power asymmetry leads to different actors along the value chain having different potential for being influenced by, or being able to influence, the lead firm of the value chain [10].

The GVC literature has thus far provided in-depth theorization of power asymmetries that arise in the relationships between actors within global value chains [24], yet the conceptualization of *power* remains vague within the literature [13, 25]. Coe and Yeung [26, p.17] define power as 'the ability of one actor to affect the behaviour of another actor in a manner contrary to the second actor's interests'. However, 'it can also reflect the ability of one actor to resist an unwanted imposition by another actor' [26, p.17]. In what Dallas, Ponte, and Sturgeon [13] propose as 'the four "faces" of power', the definition by Coe and Yeung [26] falls into what they call coercive bargaining power, i.e., power that is intentional, conflict-oriented, and resource-centred [13]. The other three faces of power are (1) agenda-setting power, referring to how, e.g., institutions and organizations can be mobilized to tilt the playing field in a particular direction; (2) preference-shaping, where the powerful are able to shape the preferences of the sometimes unknowing, less powerful; and (3) social construction, referring to how actors are disciplined to behave in a certain way through routines and practices. These four forms of power can be combined and layered 'together in complex ways across inter-firm linkages' and influence governance both upwards and downwards in the value chain [13]. Although the GVC/GPN literature has recently expanded on varieties of power (see e.g. Dallas, Ponte and Sturgeon [13] and Ponte, Bair and Dallas [25]), we pay particular attention to the concept of bargaining power. Bargaining power is regarded as the most common (yet also the most commonly studied [25]) form of power found in GVCs [27] and can be defined as 'the relative capacity of each of the parties to compel or secure agreement on its own terms' [12]. Dallas, Ponte, and Sturgeon [13] argue that bargaining power is most prominent in (dyadic) firm-firm relationships and is often associated with more hierarchical forms of governance. We suggest that the degree of bargaining power held by suppliers in Norwegian manufacturing can be crucial for understanding the potential for EnvU among these industry actors.

Being an arena for inter-firm relations, GVCs can be characterized based on the type of relations that exist between lead firms and suppliers. In our attempt to illuminate how EnvU is influenced by bargaining power, we argue that we also need to consider how GVC dynamics and characteristics influence inter-firm relationships. To account for this, we draw on Gereffi, Humphrey, and Sturgeon [10], who provide five types of value chain governance, describing the level of interactions and power asymmetries between suppliers and customers. These typologies are:

1 Markets – interactions are governed by market linkages where the cost of switching partners is low on both sides.
2 Modular value chains – suppliers deliver products to customer specifications with limited interaction between the parties.

3 Relational value chains – complex interactions between suppliers and customers that create mutual dependence.
4 Captive value chains – suppliers are heavily dependent on large customers as the codifiability and complexity of the products are often high, while the capabilities of the suppliers are low, leading to customer intervention, control, and power asymmetries ('captive inter-firm linkages') where exiting the value chain becomes an unattractive option for the suppliers.
5 Hierarchy – vertical integration where headquarters control subsidiaries and affiliate firms.

The main differences in the governance modes, therefore, relate to the complexity of interactions between buyers and suppliers, the level of independence of suppliers in the implementation of their tasks, and power asymmetries (i.e., how equal different actors are in the respective value chains), as well as how high or low the switching costs are for the involved parties. The relative bargaining power between suppliers and lead firms within GVCs differs on the basis of governance modes, meaning that different power asymmetries can be observed depending on the type of GVCs as they are characterized by differentiated inter-firm linkages [13].

Overall, we combine the concepts of bargaining power, EnvU, and governance mode in global value chains in our analytical framework and apply this framework to explore how bargaining power within global value chains influences the ability of suppliers to conduct EnvU.

Methodology

The Norwegian manufacturing industry is predominantly comprised of suppliers in GVCs. Norwegian suppliers are diverse in terms of the type of goods (final product or intermediate goods), materials they work with, where their customers are located geographically, and markets they serve. As such, it is challenging to provide a generalizable explanation of how bargaining power influences Norwegian manufacturers' ability to conduct EnvU. As the EnvU literature itself is in its nascent phase and our understanding of EnvU and how power influences these upgrading processes remains limited, we argue that an exploratory research approach is warranted. This allows for in-depth analysis of real-life phenomena where preliminary research is limited [28]. In this chapter, this phenomenon is EnvU among Norwegian suppliers in the manufacturing industry. To better understand whether and how suppliers within the Norwegian manufacturing industry engage in EnvU, we rely on semi-structured interviews, which provide detailed information on how these firms interact with their customers and suppliers and how bargaining power influences these interactions. As such, our primary source of information is 8 in-depth, semi-structured interviews with suppliers from the Norwegian manufacturing industry. The interviews were conducted as part of

Table 4.1 Industry informants' affiliations

Alias	*Informant(s)*	*Product type*	*Markets*	*Value chain governance*	*Role in the value chain*
Company A	CEO, technology and quality manager, tech. manager	Electronics	O&G	Captive/ modular	Tier 1 supplier
Company B	Head of research and sustainability	Composite gas containers	O&G	Captive	Tier 1 supplier
Company C	Factory manager	Electronics	Automotive	Captive	Tier 1 supplier
Company D	Market and development manager	Plastic components	Aquaculture Electronics Lightning	Relational Captive Captive	Aquaculture – Tier 2 Electronics – Tier 1 Lightning – Tier 1
Company E	Manager	Aluminium components	Automotive	Captive	Tier 1
Company F	Quality manager, HSE manager	Exterior plastic components	Automotive	Captive	Tier 1
Company G	Technical manager	Plastic pipes	Water and sewage Electrical industry	Captive/ modular	Tier 1
Company H	Engineering manager	Aluminium automotive components	Automotive	Captive	Tier 1

an endeavour to understand Norwegian manufacturers' strategies, actions, and plans related to a green and digital transformation of the industry. The interviewed firms are located in different parts of Norway and supply different markets (see Table 4.1). Although our informants held different positions within the respective firms, all informants were part of the firm's management, such as CEOs, sustainability managers, and factory managers. Observations from industry workshops where several of the interviewed companies participated have provided original inspiration for this study, as well as later feedback on and confirmation of our findings.

Environmental upgrading in Norwegian manufacturing

As discussed in Section "Environmental upgrading in global value chains" of this chapter, the literature on EnvU has identified four types of EnvU: process, product, organization, and end of life [5, 6]. As the scope of this chapter does not allow for a full in-depth analysis of all the empirically identified issues concerning EnvU (see a summary of findings in Table 4.2), the following sections focus on the relation between bargaining power and process, product, and end-of-life EnvU.

Process

Process EnvU [5] is central for our case suppliers and is to some extent driven by their wish to achieve cost reductions. For example, the suppliers focus a lot on reducing their energy consumption and effectivization of their processes. These internal motivations [5] drive changes that are relatively easy to achieve since the suppliers can implement these changes internally as they see fit in their organizations without a need to bargain with customers or suppliers. As such, EnvU in relation to processes circumvents possible hindrances related to a lack of bargaining power [13].

Several actors mentioned their efforts to improve their own environmental footprint through recycling rejects (i.e., wrecks or defective products from their own production). This entails recycling the rejects and using the recycled material as raw material as an input factor in the production of new products. Recycling scrap or rejects from their own production is high on the agenda for all suppliers who make their own components or products. Recycling scrap from our own production is easy since the qualities of the materials are already known, which is opposite to the use of post-consumer scrap (interviews with Company B, E, and H). Having control over the materials and their qualities ensures the same quality of the final products or components; therefore, there is no need to engage in bargaining with external actors in this regard. Changes in the qualities of the materials could result in changes in the product qualities, and suppliers cannot allow themselves to make these changes without permission from their customers due to strict requirements and specifications.

Table 4.2 Summary of findings on environmental upgrading efforts among interviewed companies

Company	*Process*	*Product*	*End-of-life*	*Summary*
A	Waste sorting; energy-saving measures; recycling of wreckage	Can at best influence their clients' choices with regard to packaging, logistics, and procurement and provide input on the products during the design phase	None	Bargaining power allows for suggestions if the supplier is included early in the process
B	Recycling of wreckage and production mistakes	Try to influence their customers' preferences regarding the products' colour (changed colour would increase possibilities for recycling)	R&D for recycling possibilities, however, no take-back schemes established yet	Bargaining power is limited, but they try to shape their customers' preferences
C	Investments in energy-effectivization solutions	Can make materials choices for own brand products, but not the components for the customers' products	Take-back for their own brand product (not components).	Limited bargaining power to establish take-back for components that form a part of the solution provided by the customers
D		Product: uses 100 % recycled plastics for aquaculture (AQ) components	Contributes to the development of a recycling scheme for AQ components	Has utilized bargaining power upwards and downwards in the VC to replace virgin material input with recycled materials

(*Continued*)

Table 4.2 (Continued)

Company	*Process*	*Product*	*End-of-life*	*Summary*
E	Use of energy-effective technologies; Reuse scrap from your own production.	Changes driven by customer requirements with regard to the content of recycled materials.	None	Lack of bargaining power to renegotiate customers' requirements
F	Waste sorting system; Use of renewable energy and energy effectivization measures; Recycling scrap from own production	None, although they see the use of more recycled materials as feasible and expressed willingness to test recycled materials if their customer had initiated it	None	Have to comply with strict sustainability requirements from the customer and have no bargaining power to renegotiate them
G	Use technology to reduce waste from production; consider energy effectivization and saving measures	Use some recycled materials in their products	None	Some customers are open to products made with the use of recycled materials, while others have to be convinced
H	Focus on energy use and effectivization; recycle production scrap	No changes due to the need to consider requirements for the materials	None	Lack of bargaining power to make changes in the products' materials

Product

Our findings indicate much fewer changes related to product EnvU among the studied suppliers, who see the specific requirements or product specifications (detailed in contracts) that they receive from their customers as a major barrier. Such specifications and information flows from customer to supplier are common in captive value chains, where suppliers have to agree to the conditions imposed by their customers [10]. Working with contract manufacturing provides little leeway for shaping end products. The suppliers also recognize a lack of motivation from customers to make any changes: 'More sustainable solutions are not in demand… Our customers [large multinational companies] around the world are not concerned with sustainable solutions' (Company B). At the same time, some suppliers see that their customers want more sustainable products and start setting requirements, for example, for a higher content of recycled materials in the products: 'Our customers say "You have to use at least 40% recycled materials"' (Company E). While this represents an example of lead firms' potential to drive product EnvU by setting requirements for the materials, suppliers find these requirements hard to fulfil while maintaining the same quality and/or features of the products and claim that customers are less willing to negotiate on technical specifications, which would be necessary to perform EnvU of products (Company E). Company F argues that 'If they [customers] want us to use more recycled materials they have to change their requirements, both regarding material qualities and appearance'. This demonstrates that customer requirements can be decisive, in line with De Marchi et al. [5], who argue that lead firms possess governance instruments for EnvU. These examples demonstrate how the lack of bargaining power to impose changes in requirements set out in contracts with their customers acts as a barrier for EnvU among several of the interviewed suppliers.

Limited bargaining power within downward linkages in the value chain also constrains suppliers' possibilities to conduct EnvU. Large amounts of the total environmental footprint of intermediate goods suppliers can be traced to the input factors (raw materials). Company B explains that '88% of the footprint of these processes stem from raw materials', which ultimately come through the factory doors. One strategy to reduce this footprint could be to replace virgin raw materials with recycled raw materials. However, as a relatively small actor in a large global industry sourcing intermediate goods and raw materials from large multinational suppliers, Company B does not have any bargaining power to influence the raw materials/input that these companies use in their production. A similar example can be found in Company A, who explains that a lack of bargaining power in relation to their supplier, combined with their supplier's lack of motivation and/or incentive to innovate in terms of, e.g., shifting from virgin to recycled input factors, inhibits EnvU. This illustrates that the ability of manufacturing suppliers to conduct product EnvU is not only influenced by their bargaining power in relation to their customers but also by the bargaining power that they have in relation to their suppliers. As such, bargaining power, or the lack thereof, is important in both the upwards and downwards linkages in GVC if suppliers are to conduct EnvU.

We recognize that suppliers' possibility to conduct product EnvU is dependent on their place in the value chain. Arguably, Tier 1 suppliers have a larger probability of being able to influence the end-customer, as they are better positioned to provide input before product specifications and contracts are drawn up, indicating higher bargaining power to influence product specifications in contracts. Company A explains that their ability to conduct EnvU related to their products depends on when they are invited, or invite themselves, to provide input on design and material choices for their customers' (lead firm in the GVC) products. As such, the company has limited and temporary bargaining power, meaning that they can alter material input in their products if they are included by the lead firm early in the design process. This demonstrates that Company A's possibility of conducting product EnvU differs depending on value chain governance modes [8]. In the relational value chain, Company A has more bargaining power and can influence product design, while in the captive value chain, the company is omitted from the design process and has to deliver on pre-specified contracts as they do not have bargaining power to influence the end product.

End-of-life

As suggested by the literature, end-of-life EnvU relates to the changes needed to 'reduce end-of-life waste flows' [6, p. 66] through the introduction of waste collection and recycling schemes, as well as facilities for reparation or refurbishment services. None of the case suppliers have any established return schemes for their products at the moment, although some have considered it a possibility and recognize the potential for value in recycling the products (companies B and F). Suppliers' position in the value chain has an influence on the feasibility of establishing return schemes. According to Company C, they are 'somewhere in the middle of the automotive value chains and therefore have no clear role regarding take-back' of the products, where they only contribute components. Furthermore, Company E identifies ownership and property rights related to products and goods made in contract manufacturing as a barrier to implementing take-back or recycling schemes, saying that 'We don't own the products…, so we have no right to get them back'. The lack of possibility to request the products back results from the established contracts and indicates a lack of bargaining power, as the suppliers cannot renegotiate these terms in the contracts [13]. An additional challenge mentioned by Company B and Company H, which will not be discussed here due to the scope of this chapter, is related to geography and how taking back products from distant areas of the world in order to recycle is not possible, nor is it sustainable.

Different markets equal different possibilities

Above, we have discussed how suppliers' bargaining power within GVCs shapes Norwegian manufacturers' possibility of conducting EnvU. As discussed, a lack of bargaining power prevents several of the interviewed companies from succeeding with EnvU, especially regarding product and end-of-life EnvU. However, our study has also uncovered that some of these manufacturers, as suppliers to different industries and part of several GVCs, have different potentials to conduct EnvU. One such example is Company D, which delivers products made from 100% recycled plastics to aquaculture. Through a combination of bargaining power and what [13] refers to as preference-shaping, Company D has encouraged their customers to accept the utilization of recycled plastics in the components they deliver. The reason for Company D's success in this regard is also based on their long-term collaboration with their material supplier to develop and verify high-quality recycled plastic materials. This preference-shaping and consequent development of a new product were possible due to well-established relations in the respective value chain and long-term collaboration based on trust. Such collaboration and trust distinguish the relational mode of governance [10]. As such, Company D has exerted a combination of preference-shaping and bargaining power both upwards (towards their customer) and downwards (towards their raw material supplier) in the relational aquaculture value chain, thus enabling EnvU. Simultaneously, company D delivers products to the automotive and lighting equipment industries with a captive mode of governance in the respective value chains, where contract requirements and standards do not enable the utilization of recycled materials [10]. Although this is the case in only one of the eight studied companies, it illustrates that suppliers are not necessarily "stuck" within one type of value chain (captive, relational, etc.) and that the same supplier can experience differentiated levels of bargaining power depending on the different value chains they are a part of. Furthermore, it underscores the temporal configurations of GVCs, which change over time, and how the potential for doing EnvU might also vary over time.

Conclusion

In this chapter, we have explored the potential for Norwegian manufacturers to conduct EnvU and how these upgrading processes are influenced by suppliers' bargaining power in global value chains. Adding emphasis to the importance of bargaining power in the EnvU process and how different governance modes in GVCs provide different opportunities for suppliers to upgrade, the chapter contributes to the EnvU literature by furthering our understanding of what hinders EnvU. Drawing on existing literature on governance modes and power in GVC, we analysed the processes of EnvU with regard to production processes, products, and end of life among Norwegian suppliers. The analysis shows that the potential for process upgrading is greater than that of product and end-of-life upgrading, as the studied suppliers have full control over changes related to their own production processes and don't need to bargain with other actors in the respective global value chains. EnvU of products, however, requires interaction with both suppliers and customers, and we have shown that the suppliers' bargaining power in these upward and downward linkages remains limited, thus hindering EnvU. This lack of bargaining power can be explained by the types of GVCs (and related governance modes [10] that the suppliers are a part of, where captive GVCs limit suppliers' potential to conduct EnvU. Suppliers in relational GVCs might experience a larger potential for EnvU as they possess more bargaining power than those in captive GVCs. However, due to the limitations of the conducted exploratory study, further research is necessary in this regard.

Theoretically, the chapter has two contributions to the literature on EnvU in GVCs. First, the introduction of power (we focus on *bargaining power*) to the study and analysis of EnvU in GVC is a novelty within the EnvU literature. Given that power and governance are key tenets of the GVC literature, we argue that the introduction of these concepts and an emphasis on how they shape the potential for EnvU in GVCs is timely. Second, by putting emphasis on suppliers in GVCs, we add to the emerging discourse on how suppliers conduct EnvU [21, 23], moving beyond the identified overemphasis on lead firms in the EnvU literature. We find that bargaining power, or rather the lack of bargaining power, among suppliers in Norwegian manufacturing is crucial for understanding the potential for EnvU among these industry actors. Therefore, we argue that the role of different forms of power and how they influence the potential for EnvU (among all actors within GVCs) should be studied further and is an avenue for future research. Although power has earlier been identified as a factor that influences the distribution of costs related to EnvU [7], the literature has paid little attention to how power relations between actors in GVCs and GVC governance modes influence different forms of EnvU.

Although the aim of this exploratory case study has not been to provide generalizations [28], we argue that our findings could be relevant outside the Norwegian context, given that the global manufacturing industry is constituted by a web of global production networks, wherein suppliers are numerous. As the studied manufacturing suppliers are part of global value chains that serve global markets, we believe that similar power relations between suppliers and other GVC actors could be found among suppliers who are part of similar GVCs located in other European countries and that their bargaining power can, thus, potentially influence their possibilities for EnvU.

Finally, we argue that this chapter has two contributions for practitioners. First, the insights provided here can contribute to improving practitioners' awareness of the importance of collaborating with suppliers and customers to improve the environmental performance of their products. Second, we believe that the examples of EnvU among the studied manufacturing suppliers can inspire others to map out their potential for EnvU, both related to their production processes, their products, and how they handle products at their end of life, and potentially initiate efforts to conduct EnvU.

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Barriers and opportunities through digitalisation

Chapter 5

Phasing the barriers to Industry 4.0

Enhancing the understanding of the challenges of digitalization

Sven-Vegard Buer, Pål Furu Kamsvåg, and Jo Wessel Strandhagen

Introduction

Since its launch in 2011, the German initiative *Industrie 4.0* has ensured an increased focus on the digitalization of manufacturing operations, not only in Germany but throughout the global manufacturing industry. The grand vision of Industry 4.0 revolves around "networks of manufacturing resources (manufacturing machinery, robots, conveyor and warehousing systems and production facilities) that are autonomous, capable of controlling themselves in response to different situations, self-configuring, knowledge-based, sensor-equipped and spatially dispersed and that also incorporate the relevant planning and management systems" [1, p. 20]. Gradually, the Industry 4.0 term has evolved into an overall label describing the next era of manufacturing, and some argue it has become a poorly defined buzzword [2]. As early as 2016, more than 100 different definitions of Industry 4.0 could already be found in the literature, as illustrated by Moeuf et al. [3].

While some Industry 4.0 showcases can be observed around the world, more than a decade after the launch of Industry 4.0, the success stories are still far apart. For many manufacturers, Industry 4.0 is arguably still mostly a buzzword and a marketing term. A recent market study in Europe shows that merely 23% of the surveyed manufacturers have started with a digital transformation of their manufacturing operations [4]. Digital transformation and Industry 4.0 are highly interrelated phenomena with overlapping content and similarities. In fact, digital transformation could be considered a cornerstone of the Industry 4.0 concept. As Industry 4.0 was branded as an enabler of keeping manufacturing in Europe and even facilitating backshoring of manufacturing from low-cost countries, the lack of more Industry 4.0 success stories might be somewhat surprising.

The potential of Industry 4.0 has been proven, and it has several stated benefits over more traditional manufacturing [5, 6]. Nevertheless, the lack of manufacturers succeeding motivates the need to gain a clearer understanding of what hinders manufacturers from reaching the Industry 4.0 vision. In order

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to develop appropriate roadmaps and digital transformation approaches, it is essential to understand the barriers and inhibiting factors so that appropriate measures can be taken.

Although a more thorough understanding of barriers can assist implementations, the investigation of barriers to Industry 4.0 remains largely unexplored in existing literature and has been pointed out as an area that merits further investigation [7]. Different from earlier studies, this study adopts a phase-based (or stage-based) approach to examine the barriers in more detail. This approach allows for investigating whether certain barriers hold more relevance early in the implementation, while others may be more relevant later in the process. We could not identify any other study in this context using this approach, and there is a need to understand how different barriers appear in different phases of a digitalization process. Consequently, the current study seeks to fill this research gap by investigating phase-based differences in the relevance of barriers to Industry 4.0. This approach to barrier investigation is similar to Klöckner et al. [8], although that study focused on energy efficiency upgrades rather than Industry 4.0 or digitalization. Notably, the cited studies in this context do not employ an approach that distinguishes between stages of decision-making, resulting in limited knowledge about the precise timing when specific barriers and drivers come into play during the decision-making process.

This study focuses on the barriers to Industry 4.0 implementation in manufacturing companies. Existing literature is reviewed to present the most frequently mentioned barriers. To add to the existing body of knowledge on this topic, an in-depth interview study involving managers from 12 Norwegian manufacturers is conducted to further investigate how these different barriers may be prevalent or change in magnitude at different phases in a digitalization process. To succeed with Industry 4.0, it is essential to focus on the right measures at the right time to be able to overcome the barriers. Thus, this study further contributes to the existing literature by proposing a barrier timeline, which in turn supports manufacturing practitioners in succeeding with Industry 4.0.

This paper is structured as follows: Section "Review of literature on barriers to Industry 4.0" introduces existing literature focusing on the barriers to Industry 4.0 and presents the most frequently mentioned barriers. Section "Research design" describes the research method utilized in this study as well as outlines the different phases typically seen in digitalization processes. Section "Phasing the barriers to Industry 4.0 in manufacturing" presents the results of this study by describing how the different barriers may emerge in different phases of a digitalization process. Section "Discussion" discusses the research findings, while Section "Conclusions" concludes the paper and highlights its contributions.

Review of literature on barriers to Industry 4.0

With the strong current focus on Industry 4.0—both in practice and in academia—there is also an increasing number of studies on the barriers to

Industry 4.0, i.e., the challenges and obstacles that companies face when trying to adopt Industry 4.0 technologies. Da Silva et al. [9] conducted a literature review of empirical studies on Industry 4.0 to investigate the implementation of the Industry 4.0 concept in companies. They identify and briefly describe 12 barriers, categorized as governmental, financial, technological, organizational, or related to human capital. Glass et al. [10] collected data from 253 German companies to identify the barriers to Industry 4.0. Mogos et al. [11] surveyed 49 Norwegian companies to study the "enablers" and "inhibitors" of Industry 4.0. The most prominent inhibitors from the study were the lack of digital competence of employees, the need for high investments, little knowledge about consequences and risks, and little knowledge about the concept of Industry 4.0. "IT security" and "Intellectual Property rights" were considered important inhibitors by oil and gas companies but not as important by discrete manufacturing companies, indicating that some sectorial, or contextual, differences apply with regards to barriers to Industry 4.0. The researchers also found, through follow-up discussions on the survey results, that there was a lack of focus on day-to-day operations and maintenance management and that companies felt they were not sufficiently incentivized to dedicate themselves to digitalization.

Raj et al. [7] identified 15 barriers to the adoption of Industry 4.0 technologies in the manufacturing sector through a literature review and discussions with experts, and further analyzed and classified the barriers as prominent, influencing, or resulting barriers to indicate the relationships among them. Jones et al. [12] reviewed past, present, and future barriers to digital transformation in manufacturing. Calabrese et al. [13] conducted a literature review to identify the enablers and SWOTs of Industry 4.0, where what is typically referred to as barriers is categorized as a "Weakness" (e.g., high investments) or "Threat" (e.g., data security). Kamble et al. [14] conducted a literature review to identify barriers to the adoption of Industry 4.0 in the Indian manufacturing industry and then validated the identified barriers with a group of experts. Finally, Senna et al. [15] conducted a literature review to identify barriers to the adoption of Industry 4.0 technologies and then used a focus group of Portuguese experts to review the set of barriers and determine their relevance in the Portuguese manufacturing industry. They proposed three actions to tackle the most relevant barriers identified: "Standardization dissemination", "Infrastructure development", and "Digital strategy".

In addition to the studies already mentioned, there have been numerous other studies that have focused on identifying and understanding the barriers to the adoption of Industry 4.0 technologies. These barriers can be grouped into several main categories, including technological barriers, such as lack of access to the necessary technology and lack of technical expertise; organizational barriers, such as lack of a clear strategy or lack of senior management support; and cultural barriers, such as resistance to change or lack of trust in new technologies. One of the most mentioned barriers is the high cost of implementing these technologies. Many companies, especially small and medium-sized enterprises, may not have the financial resources to invest in the necessary hardware, software, and personnel training. Additionally, there is often a lack of understanding of the potential benefits of Industry 4.0, which can make it difficult for companies to justify the necessary investments. Another important barrier to the adoption of Industry 4.0 is the lack of digital skills among employees. Many companies struggle to find employees with the necessary technical expertise to implement and maintain Industry 4.0 technologies. Furthermore, employees may lack the digital skills required to take full advantage of the new technologies, which can limit the potential benefits of Industry 4.0. Also, legal and regulatory barriers can impede the adoption of Industry 4.0. For example, concerns about data privacy and security can make companies hesitant to adopt Industry 4.0 technologies. Additionally, intellectual property rights can also be a barrier to the adoption of Industry 4.0, as companies may be unsure about how to protect their intellectual property and how to navigate the intellectual property rights of others. Table 5.1 gives an overview of the Industry 4.0 barriers found in the literature.

Table 5.1 Barriers to Industry 4.0

Barriers	*Description*	*References*
Technology maturity	Technology maturity refers to where a given technology is on the evolutionary curve, which could be measured using the Technology Readiness Level (TRL) or similar assessment tools/methods. An immature technology is one in which there are still flaws and could thus present unique challenges.	[7, 9, 10]
Cyber security	As a company is increasingly using digital technologies, it is essential to find appropriate systems to protect against a wide range of possible security threats. Without proper cyber security measures, the company can be at risk of data breaches or cyberattacks that can disrupt operations or compromise sensitive information. Therefore, cyber security can be a significant barrier to digitalization, as the systems must be protected from harmful threats.	[7, 9, 15]
Infrastructure	For digital technologies to operate satisfactorily, a robust infrastructure is required to enable, support, and maintain their use. This can include technical aspects such as the sufficient capacity of the network, existing hardware, or adjacent systems. It could also relate to other types of resources, such as the availability of vendors to deliver and maintain the systems.	[7, 9, 10, 13–15]

(*Continued*)

Table 5.1 (Continued)

Barriers	*Description*	*References*
Data quality and quantity	Digital tools and systems rely on data to function effectively. For instance, modern machine learning techniques, such as deep learning, are usually immensely data-intensive. However, it's not only a question of *quantity*, as sufficient data *quality* is also crucial to derive business value from digitalization efforts.	[7]
Legacy systems and lack of interoperability	Legacy systems refer to older, often outdated computer systems and software still being used. These systems may be difficult to integrate with newer technology and may not be able to take advantage of new features and capabilities. Lack of interoperability means that different systems and software are not able to communicate with each other. This can create information silos and make it difficult to access and use data across different systems, potentially inhibiting digitalization efforts.	[10, 15]
Value chain integration	A lack of integration with value chain partners can prove a significant barrier to the implementation of and being able to reap the full benefits of several different technologies. The ability to exchange data across the supply chain is important, for instance, regarding tracking and responding to changes in demand.	[7, 14]
Standards and regulations	Standards and regulations can be a barrier to digitalization as technologies may need to be adapted to current technical, legal, or industry-specific regulations or standards. This creates additional complexity and costs and can hinder the full utilization of the technology's potential.	[7, 9, 10, 13–15]
Competence	A lack of knowledge or competence related to the development, implementation, and/or use of digital technologies can be a significant barrier to digitalization and limit the organization's capability to fully utilize and reap the benefits of new digital solutions.	[7, 9–11, 13–16]
Resistance to change	Across all organizational levels of a company, there may be reluctance and resistance to change—regarding changes in how things are done and the way people work—and changes in the sense of moving from the known and familiar to something more unknown and unfamiliar. Digital solutions may cause and require such changes, i.e., that machines are operated differently, that certain tasks may no longer be necessary, or changes in people's physical surroundings, with an increasing presence of technology in the form of digital devices, different types of robots, etc.	[7, 9]

(*Continued*)

Table 5.1 (Continued)

Barriers	*Description*	*References*
Management	A lack of management support can hinder an organization's ability to fully leverage the benefits of digital technologies by limiting resources, authority, and incentives for employees to implement new technologies and by not providing the necessary priority or funding for such projects.	[9, 10]
Digital strategy	A digital strategy refers to the overall plan and approach for leveraging digital technologies to create new business opportunities or improve existing processes. A lack of a well-designed digital strategy can be a barrier to digitalization, as it can hinder a common understanding and goal, make it more difficult to prioritize and allocate resources, and hinder a process of continuous improvement of digital solutions.	[7, 10, 15]
Digital culture	The term digital culture refers to the willingness to explore and utilize digital technologies. Some organizations are reluctant to embrace digitalization, possibly because of a lack of understanding of the opportunities of digital technologies or an underlying resistance to change.	[7]
Resource scarcity	Limited resources, for instance, time and budget, are significant barriers to digitalization. In such situations, companies tend to focus on keeping up their daily operations rather than focusing on improvement and innovation, halting most digitalization efforts.	[7]
High costs	Novel technologies are typically expensive and can be a barrier for manufacturers with limited budgets. This is not only limited to the initial investment costs but also costs related to the implementation, operation, and maintenance of the solutions. Even though the technology is evaluated to have a positive return on investment (ROI) in the longer term, the initial investment might still be too costly or considered too risky for the company.	[7, 9, 11, 13–16]
Uncertain economic benefit	A lack of clarity regarding the economic benefits makes companies hesitant to invest in digital technologies. The reason for this unclarity could be due to immature technologies or limited insight regarding the actual benefits of the technology.	[7, 9–11, 13, 14, 16]
Context	Different contexts require different approaches and solutions to succeed with digitalization. Aspects such as production repetitiveness, process characteristics, and supply chain requirements may point toward the need for a tailored solution, which can potentially prove a barrier.	[11, 16]

Despite the range of existing studies, the topic of barriers to Industry 4.0 remains unexplored and in need of further investigation [7]. The studies cited above on barriers to Industry 4.0 are characterized by two main focuses. The first is the identification of barriers through literature reviews and discussions with or validations from experts, often within a specific country. Such studies tend to have a "high-level" or superficial view of the barriers, distinguishing them just by a title and short description. They lack more detailed descriptions of how the barriers make an impact. The second focus has been to rank the most prominent barriers, again with a superficial view, often by means of national empirical studies. However, there is a lack of focus on actions and measures to overcome the barriers identified, as well as a lack of detailing the barriers' influence.

Research design

This study is based on a combination of data from a literature study as well as an in-depth interview study with managers in Norwegian manufacturing companies. The literature study provided a comprehensive overview of the existing research on barriers to digitalization in manufacturing companies, while the interview study provided a more detailed and nuanced understanding of the specific barriers faced in practice.

While a few of the interviews were done in person, the majority were done through Microsoft Teams. The final sample consisted of managers from 12 discrete manufacturers with manufacturing operations in Norway. In some of the interviews, more than 1 representative from the company was present, bringing the total number of informants to 17. The total sample of informants included CEOs, CTOs, factory managers, production managers, a quality manager, an HSE manager, and a head of research and sustainability. The interviews were organized based on a semi-structured interview guide, ensuring common themes between the interviews while at the same time allowing the interviewees the chance to elaborate on certain topics, especially those relevant to their operations. The interviews were recorded for later reference. This helped ensure that the data collected was accurate and complete and that the researchers could refer back to the interviews if needed [17]. The minutes from the interviews were then sorted according to the relevant categories, based on the group of barriers from earlier studies as well as the implementation phases presented below. This helped the researchers identify patterns and themes in the data and draw meaningful conclusions from the study [18]. Additionally, the interview study allowed the researchers to add a qualitative perspective to the data and understand the subjective experience of the managers regarding the barriers. An overview of the research design is shown in Figure 5.1.

Description of phases

This study links the different barriers to the different phases typically seen in digitalization processes. These are generic phases influenced by central

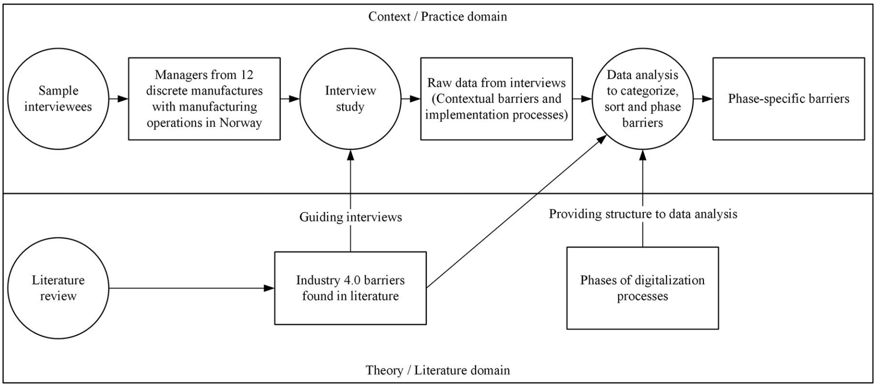

Figure 5.1 Overview of the research design.

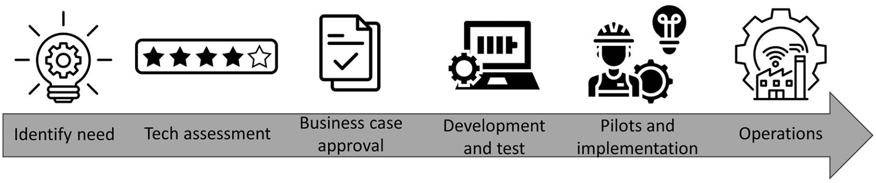

Figure 5.2 The phases of a digitalization process.

principles from implementation research, change management [19], and agile software development [20, 21], as visualized in Figure 5.2. By linking barriers with the different phases, a deeper understanding of the challenges of digitalization can be obtained. How the process unfolds depends, among other things, on the characteristics and maturity of the technology. For instance, technology developed in-house naturally requires a development phase, while off-the-shelf technology can often go straight to pilots and implementation (after the three initial phases).

Most digitalization processes are inherently nonlinear and follow an iterative and dynamic path [22]. As organizations embark on digitalization journeys, initially identifying specific objectives and digital solutions to meet those goals, they often encounter unforeseen challenges and opportunities. This could happen in all the phases described but is perhaps particularly pertinent during development and testing. The iterative nature of digitalization efforts encourages organizations to learn from their experiences, refine their strategies and goals, and continually enhance their digital capabilities.

Identify need: All digitalization efforts start with some kind of ambition or goal, and from a business perspective, it is usually related to economic gains, increased performance, and efficiency. In order to derive real business value from digitalization, the manufacturer must first identify needs or specific areas where digital technologies can be utilized to improve their operations, processes, and overall performance. Identifying needs allows the company to develop a clear plan and strategy for its digitalization efforts.

Technology assessment: This is the phase where the company assesses the capabilities and functionality of the technology in question. Companies should evaluate different technology options (and vendors) and determine which ones align with their overall business goals and budget. In this phase, it is important to assess the maturity level of the technology. Furthermore, one should ask questions such as: *What are the technical limitations and potential pitfalls? How well does the solution fit our operations and industrial context? Do we have sufficient data quantity and data quality?*

Business case approval: Before investing in new technologies, it is crucial that the company assess the compatibility of the technology—is it aligned with the overarching business goal? A business case approval typically outlines the potential costs and benefits of a proposed project or initiative. In the digitalization process, a business case approval is usually carried out because it provides a clear, objective assessment of the potential value (return on investment—ROI) that the technology or project can provide to the organization. This can help decision-makers determine whether the project is worth pursuing and can provide a basis for comparing different options and prioritizing among them. In this phase, companies often develop KPIs, which in turn can pave the way for tracking and progress assessments over time.

Development and test: The development phase entails the actual design and production of the product or solution. Development commences with the production of a prototype that facilitates testing. Today, many companies employ agile methodologies and principles to deliver products quickly, continuously testing and iterating based on input from end-users and other stakeholders.

Pilots and implementation: Pilot testing can be referred to as a small- to medium-scale preliminary study conducted to evaluate the feasibility of the technology being developed or bought (off-the-shelf products). Pilot testing is more comprehensive than the tests carried out in the development phase but is not part of the full-scale implementation coming afterwards. During the pilot test, the end-users or controllers provide feedback on the new technology, including any issues or problems they encounter. This feedback is used to make any necessary adjustments before the technology is implemented at full-scale and released to a larger audience.

Implementation is, broadly speaking, the process of putting a decision, plan, or application into effect. In the context of this study, implementation is about ensuring that the new technology is adopted by the organization and its end-users and that it works as intended. This phase includes the planning, execution, and monitoring of the implementation process—all the activities carried out to ensure successful integration and technology adoption.

Operations: To help enterprises realize their business goals by implementing digital technologies, they must succeed in getting the technologies integrated into their day-to-day operations. As part of sustaining positive outcomes after the implementation phase, it is often necessary to establish support functions to handle functionality demands from end-users, continue the process of further development, and carry out maintenance when needed.

Phasing the barriers to Industry 4.0 in manufacturing

Existing literature mentions a large number of different barriers that can hinder the digitalization process. However, it can be challenging for professionals to navigate which barriers to concentrate on. Preparing for all possible barriers can be a resource-intensive measure. Furthermore, not every single barrier will be prominent in all phases. Given that the complete digitalization process, from identifying a need until the technology is operative might take years, some barriers will be more urgent to handle. Longer implementation time can also be beneficial, as it implies more time for the company to plan the appropriate measures to overcome the barriers, thus giving the company extended time to prepare. This section describes how the different barriers may emerge at different phases in the digitalization process, giving practitioners a guideline as to when to prepare for what. Table 5.2 summarizes when, in the digitalization process, the different barriers may occur. Each of the checkmarks signals a phase-specific barrier, which is further described in the text below, marked with a code. For instance, [C11] describes how Barrier No. 11 (digital strategy) can occur in Phase C (business case approval). As illustrated in the table, there are numerous different barriers in each of the phases, suggesting that barrier management should be an important focus throughout the entire digitalization process. Some of the barriers are mostly present in the early phases; some become prominent during the later phases, while others are relevant through most of the process. The overview given in Table 5.2 indicates when barriers can occur, providing a foundation for further work, e.g., investigating how the magnitude of the different barriers changes in different phases, or creating implementation frameworks that suggest strategies to overcome the different barriers.

Technology maturity

Insufficiency and flaws might be identified during the technical assessment phase and put an end to the initiated digitalization [B1]. Furthermore, it might be difficult to estimate both costs and ROI due to low or unclear maturity levels. This could potentially make the decision-makers uncertain about the inherent potential of the technology at hand [C1]. Low technology maturity requires more development efforts and adaptation, which constitute a potential barrier [D1]. Moreover, it is difficult to measure effects during testing and piloting if the technology is unreliable and unstable [E1].

Table 5.2 Phasing of barriers

	Identify needs or opportunities (A)	*Technology assessment (B)*	*Business case approval (C)*	*Development and test (D)*	*Pilots and implementation (E)*	*Operations (F)*
1 Technology maturity		✓	✓	✓	✓	✓
2 Cyber security	✓	✓	✓	✓		✓
3 Infrastructure		✓	✓			✓
4 Data quality and quantity		✓		✓	✓	✓
5 Legacy systems and lack of interoperability		✓	✓	✓	✓	✓
6 Value chain integration		✓	✓			✓
7 Standards and regulations	✓	✓				✓
8 Competence	✓	✓	✓	✓	✓	✓
9 Resistance to change	✓		✓	✓	✓	✓
10 Management	✓	✓	✓		✓	
11 Digital strategy	✓		✓	✓		
12 Digital culture	✓				✓	
13 Resource scarcity	✓				✓	
14 High costs		✓	✓	✓		✓
15 Uncertain economic benefit	✓		✓			
16 Context	✓	✓	✓	✓	✓	✓

Lastly, a lack of sufficient *task-technology fit* due to low maturity could cause suboptimal usage and make it difficult to integrate the technology into daily operations [F1].

Cyber security

Already in the early stages, companies can be hesitant to pursue digitalization opportunities due to security concerns [A2]. Such opportunities might not even be considered because of the criticality of the affected operations or the sensitivity of the collected data. As one of the informants put it, "Machines are typically an area with poor data security. We do not want this to be a possible entry point into our corporate systems". In the technical assessment phase, the digitalization initiative might be stopped because no appropriate cyber security measures can be identified or the risks associated with the implementation of the technology are considered too high [B2]. Later, in the business case approval phase, the investments required for the designed cyber security measures might be considered too costly, i.e., the cost exceeds the estimated benefit of the digital solution. Estimating the actual costs of cyber security can be challenging, as it encompasses both technical systems and soft factors such as employee training and awareness campaigns [C2]. During the testing of the technology, new vulnerabilities in the system might be identified that can be exploited by attackers [D2]. These could be known vulnerabilities typically associated with the technology or unique vulnerabilities stemming from the specific setup at the focal company, such as the integration of systems with different security levels. In cases where appropriate cyber security measures are in place and the technology is successfully implemented and used, new developments, technologies, or regulations can challenge the sufficiency of the original cyber security measures. This can hinder continued use in the operations phase. It can also be the case that the implemented cyber security measures are too cumbersome and limit the full utilization or efficiency of the technology [F2].

Infrastructure

Lack of infrastructure becomes a barrier in the technical assessment if the proposed technology cannot be used due to infrastructural shortcomings that cannot be addressed [B3] or is considered too expensive in the business case approval phase [C3]. Later, as the technology is updated and further developed, together with other technology implementations, the existing infrastructure might exceed its capacity, preventing the company from fully leveraging the benefits of the technology [F3]. Companies must thus prioritize not only the development but also the expansion of the necessary infrastructure.

Data quality and quantity

In the technical assessment, a company could discern that the available data is of poor quality or that they simply have too little data to proceed with the digitalization process [B4]. The same problems might be identified or occur during the development phase [D4]. Furthermore, limited data volume can lead to misrepresenting results during testing and pilots, which could potentially lead to further implications [E4]. Poor data quality or insufficient data quantity could inhibit optimal technology usage and thereby be a barrier during operations [F4]. For instance, if certain groups among the end-users find the technology inappropriate for their needs and do not use it as intended, there may be a low accumulation of data.

Legacy systems and lack of interoperability

During the technical assessment, a company might discover that their legacy systems are a barrier to digitalization because they are based on outdated technology that is inflexible and difficult to integrate with new IT systems [B5]. Legacy systems are still used because they fulfill a business need or are mission-critical systems, if their investments are not recovered yet, or if the company lacks the necessary IT skills and other resources to carry out IT migration [C5–D5]. Moreover, legacy systems often lack thorough documentation, which makes such systems hard to understand, modify, and make compatible with other IT systems. The company may also be in an unfortunate vendor lock-in situation, which makes cooperation with other suppliers difficult, creating a barrier concerning the development phase [C5].

A low degree of integration with existing systems could lead to poor performance during the implementation phase and potentially end the digitalization process [E5]. Although companies naturally want to identify challenges related to interoperability as early as possible, this can be difficult in practice. Poor mapping in the initial phase, flawed testing, the introduction of new systems and technologies, and unawareness of interoperability issues in the early stages can lead to issues regarding the integration of systems during implementation and operations [E5–F5].

Value chain integration

Challenges in value chain integration can be a barrier in the technical assessment phase if there are no available solutions for integrating with the value chain partner's IT system [B6]. This barrier might also be present in the operations phase whenever the company gets a new value chain partner with incompatible systems [F6]. Moreover, even though the technical integration issues can be solved, value chain partners might be hesitant to share data, thus reducing the potential of the technology [C6].

Standards and regulations

Standards and regulations can be a barrier to digitalization in several of the outlined phases. Companies with operations that need to comply with strict regulations, e.g., from their customers or the government, need to devote extra time and resources to find compliant solutions. This may stop the digitalization process in the idea phase [A7], or the company may not find IT standards and protocols that are compliant with the technical assessment phase [B7]. Moreover, even when implemented, full utilization of the solution might be restricted by regulations on the use of certain types of data, for instance, sensitive personal data or information collected from suppliers and customers [F7].

Competence

Competence is a potential barrier in most phases, with different types of competence required to advance through the phases. Not being able to see future technology-enabled opportunities, not realizing own problems, and not being able to properly understand the benefits of the technology are all examples of how a lack of competence may inhibit digitalization processes already in the phase of identifying needs and opportunities [A8]. Then, a lack of the competence required to find the right technology for the specified need or to accurately predict the actual impact of the technology may stop the digitalization in the technical assessment phase [B8]. Similarly, business case approval requires competence to properly understand the total cost picture of any technology implementation [C8]. If the technology requires specialized testing, a lack of the competence required to design appropriate tests may turn out to be an inhibitor of a successful implementation of the technology [D8]. In the implementation phase and the operations phase, the daily use of a new digital technology will require sufficient digital competency of the operators—or technology users—to work as intended [E8–F8]. One informant described the situation like this: "We are satisfied that all of our employees have learned to use Microsoft Teams". This illustrates the range of digital competence at different companies. The importance of competence and the changing competence needs were emphasized by another informant: "We clearly see a greater need for engineering and IT expertise".

Resistance to change

It is possible that an underlying resistance to change already in the idea phase can inhibit digitalization if the resistance leads to opposition to any new idea that will possibly cause a change [A9]. Such resistance may appear in later phases as well, for instance in the business case approval phase, where it may crystallize as unreasonable attention toward any negative aspects of the technology. In this way, resistance to change may cause rejection of the business case [C9]. In the development phase, there is a risk of misalignment between end-users and developers. If functionality needs from end-users are considered by the developers, dissatisfaction and resistance could arise among the users [D9]. User-centered design and agile principles can help the organization overcome these challenges, but financial constraints often imply that the developers and change managers must prioritize which needs should be addressed [23]. In other words, it is challenging to make all end-users satisfied. Resistance to change among end-users of the technology can hinder both the piloting of new technologies as well as their full implementation [E9]. This could be due to insufficient technology acceptance among the employees, for instance, caused by limited information, limited possibilities for participation in the decision process, a perceived threat of the technology leading to staff reductions, or that the technology leads to additional work for the employees. End-user change resistance may further inhibit the operational utilization of the technology, preventing the intended potential improvement from being realized [F9].

Management

Already in the phase of identifying needs and opportunities, management can act as an inhibitor of digitalization. For instance, if management lacks a proper understanding of digitalization, they may not be able to see the potential and possible applications of digital technologies. Or management may have a too "ambitious" view of digitalization, overlooking and missing out on any low-hanging fruits [A10]. In the technical assessment phase, the process may be inhibited by an unclear overview of the organization's existing digital capabilities [B10]. Management can also stop digitalization initiatives in the business case approval phase despite the project having a positive ROI. This can occur due to competing priorities or a focus on daily operations rather than improvement [C10]. Management is particularly important in establishing methodologies and strategies for the implementation process and change management, which can ruin an otherwise successful initiative if not in place [E10].

Digital strategy

A lacking or insufficient digital strategy can be a prominent barrier to digitalization. Without a clear digital strategy, it is challenging for an organization to prioritize and allocate resources toward digitalization initiatives, hindering concept generation in the first place [A11]. Furthermore, the lack of a digital strategy makes it challenging for an organization to define appropriate goals and key performance indicators (KPIs) to effectively measure the impact and effectiveness of ongoing digitalization processes [C11]. Lacking a uniform goal or synchronized KPIs can make it hard to determine whether progress is made, as well as measuring and communicating the status throughout the organization. No clear digital ambition from the organization typically also entails that it lacks partnerships and collaboration with IT vendors, an important factor to succeed with digitalization [24] [D11].

Digital culture

The lack of a digital culture means that the organization can be reluctant to put resources into exploring the possibilities of digitalization. This means that there is little room to initiate digital ideas in the first place [A12]. Later in the digitalization process, the lack of a digital culture that encourages the use of digital technologies among the employees can result in hesitancy toward learning and using such technologies. This can result in a lengthy and difficult implementation process and make adoption challenging [E12].

Resource scarcity

Resource scarcity is a challenge faced by most Norwegian manufacturers. Accordingly, in daily operations, ensuring cash flow is their highest priority, which in turn could confine idea generation and improvement work [A13]. Resource scarcity combined with time pressure and demands for earnings can put the company in a situation where it does not have the capacity to identify digitalization opportunities. Another problem related to lacking resources is that there is often not enough budget allocated to implementation and training, an important phase whose extent is frequently underestimated. In addition to a limited implementation budget, companies often do not allocate enough time for proper testing and training, typically aiming to implement with the bare minimum of disruption to daily operations [E13].

High costs

High costs can end even the most promising digitalization processes. For instance, a mature and well-functioning technology may not even be considered for technical assessment if it is regarded as too expensive. Some companies may be forced to rule out certain technologies—or select suboptimal ones—due to high costs [B14]. If the financial resources are not in place to bear the cost, even a good business case will have to be disregarded [C14]. Unexpectedly high development costs are also a frequently mentioned barrier that could delay, downscale, or even stop the initiated digitalization. This could, for instance, be due to poor project planning, an insufficient understanding of the technology requirements, or a lack of clarification of expectations between the developer and the user [D14]. Costs may also be a barrier in the operations phase. An implemented digital solution may require significant continuous development and maintenance, which—if the costs are too high—may result in limited utilization of the technology if it becomes too expensive to keep it running [F14].

Uncertain economic benefit

Still a novel concept, it may be difficult to get a clear understanding—and proof—of the economic benefits of Industry 4.0 and its different technological applications. Moreover, without such clarity, there may be a general unawareness of many of the potential opportunities. This can be an inhibitor in the pursuit of ideas, limiting an organization's ability to identify relevant technological solutions [A15]. However, the business case approval is perhaps the most critical phase regarding the lack of clarity regarding the economic benefit. With new technologies applied in new contexts, it is difficult to create business cases that clearly state the economic benefits [C15]. If a new technology investment cannot be justified by certain returns, management will be reluctant to approve such a business case. As a result, even the best solutions may be discarded before even being put into practice.

Context

The context in which the company is operating can itself be a barrier to digitalization, but it can also be a moderating factor for the other barriers presented. The context therefore closely relates to the beforementioned barriers. In the early stage of a digitalization initiative, companies might overlook technology opportunities because of a lack of proven technology implementations in the company's own sector or context [A16]. The specific configuration of a factory might also matter, as one informant noted: "The problem is not necessarily the technology itself, but with our factory setup, Industry 4.0 does not fit properly. If we were to build a new factory, Industry 4.0 would be relevant and useful. But the way the factory is today it is difficult to see a positive cost-benefit of Industry 4.0". An initiative might also stop in the technical assessment phase if it is found that, although the specific technology in general is mature, there is a low technological maturity for the specific technology in the given context [B16]. For instance, a vision system for quality inspection may work well in a highly repetitive production environment with standard products but be less technologically mature in a non-repetitive environment with customized products. In the business case approval phase, the estimates of the benefits and drawbacks of the identified technology might be inaccurate if they are based on implementations from other sectors with different contextual factors [C16]. Similarly, differences in context can potentially be a barrier when hiring developers with a limited understanding of the peculiarities of the context that companies operate in, for instance regarding supply chain requirements, documentation requirements, or security requirements [D16]. In the implementation phase, aspects such as existing work procedures and routines, workplace culture, existing machinery, or the general *technology acceptance* in the sector could make the implementation more difficult [E16]. Context may also become a barrier in the operations phase. For instance, specially tailored solutions based on the company's context might have been less tested and thus more unreliable. It is likely also more difficult to find external support for updating and maintaining these systems [F16].

Discussion

As most manufacturing companies still struggle to succeed with the digitalization of their operations and the consecutive transformative changes, there is a need for a better understanding of the factors that inhibit this process. This knowledge will be important to create effective roadmaps and strategies for digitalization. Digital transformation is not a one-time event but rather a continuous process. As technology continues to evolve, companies must be flexible and build organizational capabilities that enable them to take advantage of the opportunities.

We see that existing studies have focused on identifying and listing different types of digitalization barriers [9–11, 13, 14]. This has been an essential first step, and we argue that now there is a need to be more specific as to what these barriers entail and when you can expect to meet them in a digitalization process. A general awareness and understanding of the barriers do not necessarily help companies overcome them; however, this paper's phased approach to comprehending the barriers can better enable the development of mitigation and action plans. The phase-specific analysis presented in this paper could further be integrated with investigations of causal relations among barriers [7]. Other studies have further ranked the importance of the barriers based on quantitative surveys [15]. While such rankings contribute to a better understanding of which barriers are most prominent on a national scale, we argue that because of the unique context and peculiarities of each manufacturer, it is difficult to exactly predict which barriers will be most prominent for the individual case. Hence, a company should think strategically about all the barriers as early as possible and prepare for them, but at the same time, be aware that specific barriers will be most prominent in different phases. While academics might find it most interesting to read Table 5.2 row by row, focusing on each individual barrier, practitioners may find it more useful to read the table column by column, as it gives an indication of which barriers one should prepare for in each phase.

Through inspecting the barriers presented in Table 5.2, it is evident that the barriers themselves are different in nature. Some are "self-imposed" barriers, for instance, that the company does not see a positive ROI from the technology or that the company has a formal or informal policy not to pursue digitalization opportunities. Such barriers can be perfectly reasonable, as digitalization in itself should not be the goal. Digitalization projects should present good business cases, either through improving existing processes or creating new, innovative processes. However, a lack of digital ambition because of limited knowledge or an inappropriate understanding will make the company fall behind in the digital race and, possibly in the long term, hamper the company's competitiveness.

Conclusions

This paper has focused on providing more knowledge regarding the barriers to digitalization. By linking the barriers to the different phases of a digitalization process, a total of 62 phase-specific barriers have been described. By focusing on phase-specific barriers rather than more generic barrier groups, more understanding of the potential challenges can be obtained, and companies can be better prepared to face them.

This study contributes to the development of a theoretical framework for understanding the factors that influence the successful adoption and implementation of digital technologies. Regarding the barriers that hinder a desired digitalization process, there is a need to better understand how these can be overcome. Existing research on barriers has so far had a somewhat superficial approach to identifying and analyzing the barriers. This paper has integrated the perspectives from the literature on Industry 4.0 barriers [7, 9–11, 13–16] with the literature on implementation research, change management, and agile software development [19–21]. In this way, we contribute to a more complete understanding of how barriers influence digitalization processes. Compared to earlier studies, this study specifies when each of the barriers can be expected to occur; thus, it provides more details than existing analyses and a more nuanced perspective. By describing the barriers in more detail, this study contributes to a deeper understanding of them and when they are expected to appear.

In general, barrier analysis is an important tool for organizations to better understand the challenges they will face when trying to implement new technologies. It can support practitioners in identifying the factors that are preventing a full realization of the benefits of the new technologies and can be a support for developing strategies to overcome them. The analysis presented in this paper takes it one step further by analyzing when, in the digitalization process, these challenges may emerge. This study shows that some of the crucial barriers may emerge in the later phases of the digitalization process. Organizations should be aware of these early and prepare to avoid later failures or excessive costs. As discussed in earlier research [25], addressing such barriers early is important, as the further you are into the digitalization process, technology reversal can become increasingly costly. This study can support organizations in developing focused action plans for taking preventive actions or handling barriers as they arise.

The empirical findings in this paper are based on interviews with 12 Norwegian manufacturers. Although we expect that these findings are relevant and applicable outside of our sample, we cannot for certain claim generalizability of these results. Further research in other settings and contexts is encouraged. This study presents a technology-agnostic analysis of barriers. Future studies can focus on specific technologies to identify whether some barriers increase or decrease in magnitude based on the technology. Finally, there is a need for investigating the relationships between the different barriers to better understand how they interact and best can be overcome.

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Chapter 6

Digitalization and sustainability

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Introduction

The linkage between digitalization and sustainability has received much attention in recent years from both the academic and practitioner communities. However, rarely studies have approached the issue from an integrated supply chain or sales and operations planning (S&OP) perspective. The traditional, inward-looking S&OP process, which entails a cross-functional team of managers balancing demand and supply and generating an integrated set of tactical plans (Jonsson *et al.*, 2021), is viewed as a structural barrier to a transition for sustainability. Participation from external stakeholders in tactical planning is recommended by Roscoe *et al.* (2020) as a means of overcoming any resistance to sustainability – sustainable sales and operations planning (SS&OP) for realizing the triple bottom line. This they refer to as the voice of secondary stakeholders (VoSS): "an external force that challenges the decisions for disruptive and pro-environmental social change".

Making decisions about sustainability necessitates a careful balance, rather than a choice between pro-environmental societal changes and costs. Even if there is a lot of pressure from external stakeholders for sustainability, decisions made at SS&OP meetings should still be commercially viable and competitive. This means the VoSS needs to be complemented by viable alternatives created through digitalization that can ensure continued success in the market. In this research, we view digitalization as an instrument to empower the SS&OP processes through information visibility to have the resources and capacity to balance economic, social, and environmental objectives effectively. That fits well with the vision of digitalization presented by Ghobakhloo (2020), that is, purposefully leveraging modern digital technologies to advance firms' capabilities.

Given the preceding, this research seeks to answer *how traditional S&OP practitioners can make the leap to digitally enabled SS&OP by coordinating their activities internally as well as with those of their suppliers and customers*. The research question unfolds into three objectives. First, we identify the priorities and digital initiatives for SS&OP, i.e., the many activities within the

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SS&OP processes that can create resources and capacities for sustainability. Next, we elaborate on the roadblocks to the digital transformation of planning for sustainability. Finally, we conclude by providing insights into addressing the roadblocks.

Background

Digitalization for SS&OP

As a tactical planning process, S&OP can act as a driver and platform for integrating sustainability decisions (e.g. avoiding supply chain surplus and waste while maintaining service levels, enterprise resource planning (ERP), green procurement) in supply chain management by translating long-term sustainability goals to short-term actions and achieving planning consensus across internal and external stakeholders (Azevedo *et al.*, 2021). The capability of digital technologies is to create accurate information and allow integration and transparency between the stakeholders in the supply chain, i.e., seamless information exchange within and across organizations and organizational levels, that enables and supports sustainable decisions in the S&OP process (Roscoe *et al.*, 2020). The potential of digitalization lies in its ability to improve demand and supply plans and create a more accurate demand response that takes into account the sustainability needs of customers. This includes monitoring supply chain activities and taking proactive actions before environmental or social issues occur. However, the technologies in isolation cannot have as much of an impact on the sustainability agenda or facilitate an SS&OP process since the collaboration and communication pattern between the stakeholders must first be in place (Hadaya and Cassivi, 2007; Dao *et al.*, 2011). I4.0 technologies are to play a crucial role in this for SS&OP, as these are viewed to enable supply chain integration and coordination in sustainable supply chains (Di Maria *et al.*, 2022; Toktaş-Palut, 2022).

Transition, transformation, and open innovation

Digital transformation has lately become a buzzword both in academia and practice. Commonly enough, “Transition” and “Transformation” are not seen as mutually exclusive and are often used interchangeably; both of them resonate with the idea that, given the uncertainties of today, business-as-usual is not sustainable and requires change (Hölscher *et al.*, 2018). Transformation, however, is neither synonymous with nor a separate change process from transition. *Transition* is broader and more fundamental in scope; it refers to a shift from one socio-technical system to another (Child and Breyer, 2017). *Transformation* is instead only a typology or one of the pathways of transition (as opposed to the other transition pathways such as reconfiguration, substitution, and re/de-alignment) that refers to a disruptive change, completely altering the stability landscape in ways that build into a new type of system and challenge the status quo or conventionally held assumptions, and reorienting the direction of innovation activities (Geels and Kemp, 2007; Geels and Schot, 2007; Child and Breyer, 2017). In order to undergo a successful transition for SS&OP, and especially via a transformation pathway, businesses need to be able to look within and beyond their own organizational boundaries and be unencumbered by internal structural lockins and path dependencies. When managers are "immersed in social structures that strongly impact their interpretations, intentions, and rationales", they are less likely to "(un)intentionally alter these very structures" for transformation to occur (Englund and Gerdin, 2018). Open innovation could be the key to helping organizations work together to identify new applications for complicated scientific findings they could not have found on their own through internal innovation programmes (Bertello *et al.*, 2022). Networking with other businesses, research centres, and universities is fostered through open innovation strategies realized through participation in public-funded R&D projects (Nishimura and Okamuro, 2011; Santos, 2015).

Methodology

Due to the multiple facets of the research question, it was split into three separate objectives. The first objective was to identify the status quo and the more disruptive potential in SS&OP driven by digital technologies. The second objective was to uncover what holds back or slows down businesses from embracing transition (especially disruptive or transformative transition) towards sustainability, or SS&OP. The final objective was to postulate how the barriers or roadblocks to this transition could be overcome. In light of the foregoing, this research used a multiple case study design (Yin, 2018). Six Norwegian companies (see details in Table 6.1) were purposefully chosen because (a) they are partners of a large-scale Norwegian public-funded research consortium/centre pursuing a digitalization and sustainability agenda; (b) they are advanced globally competitive manufacturers serving industrial customers; and (c) each operate in a different industry, providing a breadth of understanding of the problem of interest.

To address the first objective, (a) we engaged with the case companies through three rounds of reflective workshops, and (b) we analysed secondary data from one-on-one meetings between senior managers of the research centre and the case companies, as well as the reports on the ongoing and future innovation projects of the centre. In the workshops, senior managers of the various supply chain functions (production, distribution, procurement, and sales and marketing) were involved from each of the case companies, which also reduced the chances of any individual's biases affecting the findings (Pagell and Wu, 2009). Especially, to assess the disruptive potentials in

Table 6.1 Description of the companies

Companies	*Manufacturing sector producer*	*No. employees*	*Responsibility of the participating managers*
CASE 1	Consumer goods	1.300	Production planning and customer service. Logistics planning. Technical manager, production. Sourcing and supply.
CASE 2	Industrial equipment	105	Managing director. Production planner. Change management and quality.
CASE 3	Composite containers	130	R&D head, production. Sales. Purchasing and logistics. Production.
CASE 4	Industrial assemblies and components	490	Production. Planning head.
CASE 5	Electronic and mechatronic assembly	350	Chief executive officer. Purchasing and logistics manager. Production manager. Sales and marketing director.
CASE 6	Defence products	840	Material engineer. Sales and marketing. Operations head.

SS&OP, we jointly reflected on the emerging technologies with respect to the case companies' sustainability priorities and the associated I4.0 literature.

The second and third objectives were addressed through an interpretive analysis (Lincoln, 1995) of the data gathered by "reading between the lines" and "interpreting silences" (Poland and Pederson, 1998), especially building on the companies' "knowing in practice" (that is, tacit, automatic, and spontaneous) and "reflection in actions" (that is, to critique or reinterpret their experiences and practices) (Schön, 2017). This entailed carefully focusing not only on what practitioners said but also on why they said it, their world views, and exposure to emerging technology-based opportunities in practice and theory. Thus, the process also required cross-reading and contrasting relevant literature based on the responses we received during the workshops, as well as gathering our observations during consortium meetings for interdisciplinary knowledge and experience sharing between industry and academia partners.

Empirical reflections and actions for SS&OP

While the conventional S&OP process has been viewed as myopic and to be majorly focused on efficiency and cost reduction by balancing demand with supply (Jonsson *et al.*, 2021), SS&OP is viewed to seek harmony between economic, social, and environmental objectives. For example, demand planning will also be influenced by the voice of supply chain (VoSC); supply planning would need managers to consider the kind of materials needed as well as the suppliers from whom they should purchase (Ginsberg and Bloom, 2004; Lin and Niu, 2018). In the following subsections, we uncover the many priorities facing resources and capacities for SS&OP processes that gain from digitalization.

"You don't get a green transition with a red bottom line" Case 3

Procurement and material requirement planning

Sourcing of green materials

Green materials are those that are safe for the environment and human health, as well as those that can be recycled or reused without depleting finite natural resources (Ellen MacArthur Foundation;[1] Oh *et al.*, 2009). Sustainable design and planning often focus on the economic implications of using green materials. Case 2, for instance, keeps track of the steel that is to be used in a global database, together with information such as whether or not it is recycled, where it was obtained, and a blacklist of suppliers to avoid. Certain products' CO_2 footprints or sustainability features may be specifically requested by customers, prompting manufacturers to examine raw materials. Case 5, for example, in the electronics industry, sees a shift away from hazardous materials such as polychlorinated biphenyls. In addition, there are industrial processes, as Case 1 finds in the consumer goods industry, that enable the separation of materials at end-of-life (often steel frames or foam) and the examination of chemical compositions for enhanced reuse. Case 6 especially mentioned that steel expertise is important for them, and while they are building internal expertise, they are also looking out for strategic support from the partnering research consortiums and through relying on PhD research, learning about the best practices, and addressing the issues at the interface between product development and industrialization. The composite container market has also found that customers want products that work with their efforts to reduce their environmental impact. For example, some of the customers in Case 3 require composite containers to work with dimethyl ether (DME), an alternative to liquefied petroleum gas. Nonetheless, it was observed that the companies, even though they have been focusing on green materials, were less involved in or aware of the I4.0 technologies such as blockchains that could support the operational aspects of green purchasing or sourcing reusable and recycled materials, and in turn, SS&OP such as supplier certification, supplier compliance and auditing, Tier-2 suppliers' environmental practice evaluation, etc. (Vijayvargy *et al.*, 2017; Ghadge *et al.*, 2022).

"I don't see Blockchain in the next 20 years" – a manager from Case 6

Ethical sourcing

The social consequences of supply chain decisions are just as important as the economic and environmental ones, making this a critical component of SS&OP. It is becoming increasingly important for advanced manufacturers, such as those that make composite containers or advanced tools, to take responsibility for their suppliers and customers, as well as to gather information about the owners and other businesses with which they are affiliated, to ensure that the operations are both ethical and responsible. For example, artisanal and small-scale mining can pose a number of risks, including exposure to poisonous substances, poor working conditions, corruption and exploitation, and the worst types of child labour (Elenge *et al.*, 2013; Banza Lubaba Nkulu *et al.*, 2018; Maiotti *et al.*, 2019; Mancini *et al.*, 2021). These are all against the collaboration guidelines of the case companies in our study, yet they submit to their technological restrictions on supplier monitoring activities. In fact, Case 1, in the consumer goods industry, places a special emphasis on maintaining the same ethical standards in Asia as they do in Norway. To that purpose, the firm performs frequent inspections as well as external audits of the places in concern, but thus far has not engaged in blockchain implementation programmes, which are emerging as a crucial approach for transparency and ethical sourcing (Kshetri, 2022). Case 1, in fact, sees many challenges with it, such as internet connectivity issues with some of the suppliers from the developing countries. Also, not all suppliers (the smaller ones especially) are capable of or are willing to make such investments, and it could be very difficult to get them on board. Also, they emphasized that they relied on the existing practices and their effectiveness in addressing the problem and didn't feel the need to invest in such new technologies.

Production planning and scheduling

Alternative approaches and processes

Since it's not easy to refurbish electronic items, Case 5 has shifted its attention to minimizing scraps, such as using nitrogen in the soldering process to reduce slag and waste. Reducing waste and raw material consumption is also an important element of SS&OP (Roscoe *et al.*, 2020). Additive manufacturing (AM) is emerging as an alternative approach to environmental sustainability (Ford and Despeisse, 2016). AM produces products of complex shapes with high precision, layer by layer, leading to much less raw material waste as compared to the conventional manufacturing process; it also promotes the use of new, smart, and environmentally friendly materials, as well as reduces energy usage and machine emissions (Javaid *et al.*, 2021). Within the defence industry, agreeing on their limited knowledge of AM internally, Case 6 has an active collaborative project running on AM of energetic materials. Also, the managers from Case 2 stated that "AM is more of an interesting tool/technology than a 'dangerous' competitor to complex machining" and see a potential for innovation projects with the research centre looking at AM towards products with high tolerances, such as combining AM with embossing. In Case 1 (consumer goods industry), the use of animal skin for covers leads to environmental challenges such as reliance on red meat or the harmful implications of the chrome tanning process. Case 1, therefore, has now begun 3D knitting that not only addresses both the aforementioned challenges but also reduces the waste of materials from cutting and trimming. Also, in Case 1, with the upcoming circular business models such as rental business models, more of a "design for disassembly" is being encouraged, where all components and material fractions can be easily separated, recycled, or reused. In fact, Case 5 noted that the research centre has an innovation project on "Circular components". Though the cost of reprocessing used components into new raw materials is high, the market can turn that way with new environmental regulations and circular components. The potential of 3D-printing the critical electronic components (Hong *et al.*, 2021), however, did not emerge in the discussions.

Focus on energy

Government policies regarding reducing greenhouse gas emissions or increasing the use of non-fossil power sources can influence the production processes and priorities in matching demand and supply while balancing the social and environmental objectives and implications. Environmental performance includes energy and resource use, as well as a company's footprint of operations like air emissions and chemical residues; green energy or reduction in energy use is therefore viewed as an important measure of SS&OP (Savitz, 2013; Roscoe *et al.*, 2020). Green heating and cooling steering systems, as used in the electronics industry by Case 5, are an example of such a pro-environment initiative within the production process. The system helps to decide where heating is needed and where the system needs to cool down and transfer heating to different locations of the factory. The use of electric vehicles for transportation within factories is becoming more common, as evidenced by the case companies. However, the role of I4.0 in energy saving, such as AM in reducing energy usage and machine emissions (Javaid *et al.*, 2021), or the use of big data analytics in a traditional set-up of energy-efficient manufacturing (Wang et al., 2018; Chang et al., 2022), didn't yet emerge as an ongoing practice. AM, for example, provides precise layer-by-layer addition of raw materials and enhances productivity, reducing CO_2 emissions, energy demands in production, and material needs. Because AM facilitates local manufacturing, it lessens planners' dependence on shipments from elsewhere. On the other hand, big data analytics can evaluate the associations between machine parameters to create predictive models that lead to optimized machine energy efficiency and reduced energy consumption. Consequently, the implementation of such models can lead to the establishment of an energy-efficient production process, thereby facilitating effective planning and resource allocation. This is particularly beneficial in the energy-intensive semiconductor industry.

Analytics and decision support

Traditionally, the inventory and capacity decisions of S&OP are constrained by the pricing flexibility in sales (Grimson and Pyke, 2007). Now, with the sustainability agenda, the decisions further require considering the environmental and social implications (Roscoe *et al.*, 2020). The large customers of Case 1, especially those from Sweden, Denmark, Germany, and Australia, request a great deal of information about sustainability and life cycle assessment. Such needs from customers require better integration within the organization and across the supply chains, as well as the advanced analytics capability to process diverse information from multiple sources (or big data) for optimal decision-making (Schlegel *et al.*, 2020). The companies observed that big data is not integrated with their ERP system. Some technologies to integrate forecasts, plans, and output could be useful. In some cases, inventory is manually tracked and entered into the ERP system; in others, as in Case 3, scanning barcodes is usual, but more advanced Kardex/Hoexts digital storage systems are also being used, such as in Case 2. In the consumer goods industry, there could be several thousand models, combinations, and variations, and maybe five to ten different main parameters that have to be considered during the processes, which makes it challenging and runs the risk of generating delays or deviations. Moreover, for Case 1, shipments have to be booked early for space, and a delay can cause a major problem in timely shipping. Case 4 found it could be useful to have the technology to automatically generate and assess proposals on the best scenarios/re-planning of a line, considering inventory position for the particular product, demand at the moment in a queue, availability of the lines, profiles available, etc., without having to have an emergency meeting. Big data and digital twins have a crucial role in scenario analysis and replanning for the triple bottom line (He and Bai, 2021; Xu *et al.*, 2021). Advanced simulations support minimizing material wastes and those that emerge from production errors (Ricci *et al.*, 2021). A digital twin is being used by Case 5 to better utilize their resources and for flexible production – to assess the space required during production to ensure a continuous production flow. The current practice is to set the priorities manually: what is to be produced first, second, and next. While all the information is available in the system, it is difficult and time-consuming to manually look into all the information and make an optimal plan. Digital twin-based planning, which also involves analytics and optimization, can detect and predict demand and supply variabilities, allowing for the prevention and reallocation of waste towards the realization of zero-waste value chains, which in turn has a significant impact on inventory and capacity decisions for sustainability (Sengupta and Dreyer, 2023). Also, some companies are practicing and promoting the sharing of manufacturing resources and shared factories (Li and Jiang, 2021), and in turn, collaborative consumption for sustainability, which could further be expanded with the digital twin technology (Wang *et al.*, 2021). For example, Case 4 has extra capacity in extrusion that is offered to other manufacturers who have a shortage in production capacity, but such sharing thus far has not been operated with digital twins or protected through blockchains (Li *et al.*, 2021), which is likely to be the case in the future. Case 3 and Case 4 have also joined hands in a collaborative machine-learning and analytics-based project with the centre for exploring the possibilities with continuous capture of data throughout the chains of processes and optimizing manufacturing variations.

Distribution and transport planning

Green transport

SS&OP requires not only following upstream sustainability goals but also downstream. The potential use of environment-friendly transport modes for distribution (Ageron *et al.*, 2012; Roscoe *et al.*, 2020) is gaining more attention and must be considered in planning. Though green modes are far from common, where cost efficiency is still the dominating factor in distribution, several initiatives for sustainability are observed in the industry. Case 4 stated that many customers in the industrial assemblies and components industry are keen to know the CO_2 footprint for some of the products, though, to date, cost plays a bigger role than sustainability. Regulations have to force the original equipment manufacturers (OEM) by imposing duties or penalties that make non-environment-friendly modes more expensive; "*business will only be driven by cost and cannot be left to the conscience of people*". Further, as Case 3 observed, container ships are not a very sustainable option, so some companies have started to look into *ammonia or liquid hydrogen-based* ships (Ash *et al.*, 2019; McKinlay *et al.*, 2021), which could be the future. The integrated order management system with the logistics vendor that is being developed by Case 1 is also likely to support more fuel-efficient scheduling of shipment and distribution; the system will provide access to the forwarders of the purchase orders, the supply status, or delays with the material vendors, and can plan what is likely to be shipped months ahead.

Supply chain miles and localization

Localization, or local production, is not only viewed to be more resilient and robust than global supply chains but also seen to fulfil environmental and social objectives (Sarkis, 2020). Localization entails low resource and energy consumption and less waste. As Case 3 observed, after the pandemic that exposed the vulnerabilities of global supply chains, many US and European companies are reconsidering their sourcing strategies for Asia. Producing near the customers addresses the major distribution-related sustainability challenges and therefore becomes a crucial element of SS&OP. AM is viewed as having the potential for supporting localization (Ben-Ner and Siemsen, 2017; Verboeket *et al.*, 2021), even though at present it is mostly being considered by the case companies for tool manufacturing or prototypes and not the main product. Nonetheless, as previously mentioned, the consumer goods industry has started using 3D knitting to replace leather in covers. Further, with AM, Case 2, and Case 3, it also becomes easier to print advanced equipment and start manufacturing facilities near the customers, even internationally, with less hassle of transporting the factory set up from the home country.

Ease of trade and regulations

International trade requires complex cross-border paperwork and authentication that leads to increased transit time, supply delays, inventory management problems, and, in turn, waste. This is observed to be a massive planning and operational challenge for most of the case companies supplying international customers. The process is necessary given the illegal activities (such as drug transport) that are common along the sea routes and the need for identifying and controlling where traded goods come from and whether they have been illegally obtained (Lund *et al.*, 2019). Though not common yet, blockchain has the potential to overcome such a challenge and ease international trade by enabling transparency and rapidly authenticating and preventing illegal practices (Herold *et al.*, 2021). Such solutions, therefore, have a social impact on society by lowering fraud and illegal activities, as well as improving the efficiency of cross-border operations. But as Cases 2 and 3 reflect, such a transformation is largely dependent on the initiatives of large logistics companies and the support from all of the stakeholders in the supply chain.

Sales planning

Demand assessment

Case 3 has integrated sensors in their products that, for example, monitor gas levels and impact and can be tracked through a GPS connection for fleet control. This allows for the analysis and prediction of customer behaviour and product usage patterns. Such product in-use data can provide critical information on potential future demand and enhance forecasting accuracy, which can benefit SS&OP for reduced inventory accumulation and more precise supply planning. Effective supply planning has significant sustainability implications, including accurate levels of production (which reduce unnecessary power consumption or waste of materials), energy required in storing materials, and emissions in transportation, which improve SS&OP and the triple bottom line. (Andersson and Jonsson, 2018; Roscoe *et al.*, 2020).

Return and maintenance

The return of products has environmental implications as it leads to unnecessary return shipping and other waste. Case 1 has developed an augmented reality-based application that allows customers to have close-to-reality visual experience of how the product would look or fit in their facility and thus help them make more confident online purchase decisions. Retailers who adopt an AR strategy may see increased inventory turnover, higher average sales, more related item sales, and better customer service outcomes as a result of making online purchases feel as good as physical purchases. This, in turn, may lead to fewer customer returns, which in turn leads to less emissions and energy waste in unnecessary return shipment (Berman and Pollack, 2021).

Roadblocks and the way forward

A peek into the roadblocks

Upon discussions with the industry, it was evident that each of the case companies is prioritizing sustainability and has engaged in sustainable practices of some form. Nonetheless, we observed that, by and large, the vision or actions towards digitalization, at times, are limited by their perceptions and exposure and, at times, by their concerns about technology readiness levels and industry trends. We synthesized these into four factors that emerge as roadblocks to the transition towards SS&OP (see Figure 6.1): cultural factors

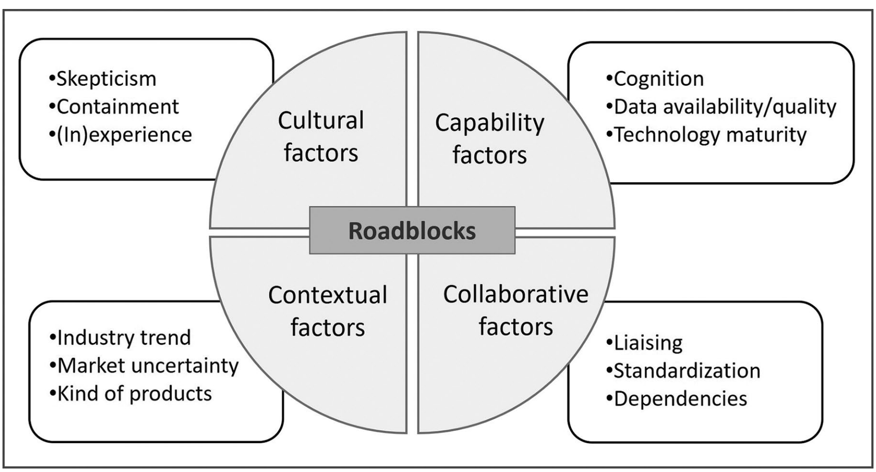

Figure 6.1 Roadblocks to SS&OP.

(scepticism, containment, and (in)experience), capability factors (cognition, data availability/quality, and technology maturity), collaborative factors (dependencies, liaising, and standardization), and contextual factors (industry trend, market uncertainty, and product complexity).

From a cultural point of view, some of the case companies appeared interested but "*sceptical*" about the potential of digitalization or of making mistakes as early adopters, while some appeared "*content*" with the status quo and did not see the need to make any changes or investments in I4.0-enabled sustainable transitions. When asked about their difficulties with digitalization for planning and sustainability, most of the companies admitted that they "*lacked experience*" with new technologies, citing their lack of familiarity with the new sources concerning big data, the implications of digital twin-driven planning, or the implications of blockchains. More proactive involvement in digital transformation for sustainability is obscured by a lack of understanding of the scope and approach, which in turn varied between companies based on their early vs. late adoption culture and technology-intensive mindset. Further, from a capabilities point of view, it appeared that "*cognition*" (that is, the managerial or organizational capacity to reason, learn, feel, and envision that is shaped by social interactions and environment or comparison with others (Carayannis, 1999; Tsinopoulos *et al.*, 2018; Wascher *et al.*, 2018)) of the role of technology was critical in deciding upon the adoption and initiatives. Rather than seeing the digitalization of S&OP as a transformation enabler, challenging the status quo and developing new processes and approaches to business (Jonsson *et al.*, 2021), most organizations saw it as a functional enabler, facilitating the transition from analogue systems to digital or automated ones. Big data analytics is viewed as a potential game-changer in supply chain planning (Xu *et al.*, 2021). Managers may be persuaded by this idea to invest in big data analytics technology before determining whether or not it is useful in their specific business setting or assessing whether or not they have the necessary capabilities (Xu *et al.*, 2021) to gain access to new data sources and other such requirements. Some of the case companies didn't know what to do with the large pool of data they already had or about any new sources of useful data; concerns of "*data quality*" and survival bias emerged as important. Survival bias occurs when only the "surviving" observations are considered and those that are missing are ignored. Furthermore, some companies failed to recognize the potential for out-of-the-box solutions for planning through I4.0 because the technology has not yet "*matured*" and there are rarely any successful large-scale cases to rely on.

From a collaborative perspective, "*Liaising*" may be difficult because not all stakeholders in the network stand to gain equally from the same policies (example: see Wang *et al.*, 2021 on designing blockchain-enabled supply chains), and not all upstream providers may be ready or able to make the shift to a digital system (Kohnke, 2017). For example, defence customers may be reluctant to extensively integrate with their suppliers due to security concerns. Further, "*standardization*" of the systems is necessary for such integration across the supply network, which is currently seen as a potent roadblock; different suppliers use different systems and software. Typically, the larger business in the network sets the rule and the smaller business adapts to their systems, but this again creates interdependencies among them. Adding to the debate over supplier development vs. supplier switching (Friedl and Wagner, 2012) in response to changing needs and strategic priorities, investing in digitalization for supplier integration and, in turn, forming "*interdependencies*" can make supplier switching more difficult when necessary. Additionally, the context – that is, the "*industry*", the "*market*", and the "*kind of products*" – also played a role in how the case companies approached digitalization for sustainability initiatives. Some of their clientele is eco-conscious, and they expect them to follow sustainable practices. Industries that rely heavily on technological advancements were the most interested, as they tend to be technological pioneers who value innovation over incremental improvements. Moreover, some case companies could make the switch to sustainable alternatives with less difficulty than others; for example, the consumer goods company could switch from using leather for its product covers to using 3D-processed covers, while the industrial equipment company recognized the possibility but needed external innovation projects to investigate how the technology might support printing high-tolerance products.

A way out and the way forward through open innovation

In the preceding sections, from the SS&OP perspective, we observed that the companies, while keen on transforming for sustainability through digitalization, their current practices and exposure have limited their approach largely to transition pathways that involve intra-organizational measures such as the use of green vehicles on premises or energy efficiently adjusting heating and cooling off in the factory, and are seldom seen to engage transition via truly transformation pathways (which involve reorienting the direction of innovation activities and mandate inter-organizational measures such as implementing blockchain solutions for ethical sourcing). Successfully transitioning to SS&OP requires addressing the roadblocks identified. Adding to Roscoe et al.'s (2020) emphasis on the importance of including external stakeholders in the planning process to create pressure for sustainable planning, we argue for "Open Innovation" that emerges as a potential strategy to overcome the roadblocks by looking beyond the status quo, traditions of knowing-in-practice (Schön, 2017), and structural lock-in for SS&OP. Radical approaches require novel ideas and are often realized through open innovation, which points to a new paradigm of "knowledge generation, sharing and management" (Mamasioulas et al., 2020).

Associating with stakeholders across supply chains, participating in workshops for reflection-in-action (Schön, 2017) with other organizations, and conducting research in various aspects in consortiums/centres, such as cross-organizational collaborations, incentive mechanisms, win-win strategies, and the potential and impact analysis of the I4.0-enabled functionalities for SS&OP, are all necessary to address the *cultural* and *collaborative factors* causing the aforementioned roadblocks. They warrant open innovation because it may be challenging for the core organization to pursue the same independently through in-house innovation programs. Participating in publicly funded large-scale R&D consortiums of regional businesses, research organizations, and academic institutions (Bertello *et al.*, 2022) could result in a 360-degree perspective and more informed strategic efforts and investments. Further, the capability and contextual factors could be addressed with specific technical research projects in collaboration with academic institutions with state-of-the-art infrastructure and experienced research teams of senior professors, PhD research scholars, and postdoctoral fellows. An ecosystem of evidence-based management practice is established: "Seasoned practitioners sometimes neglect to seek out new evidence because they trust their own clinical experience more than they trust research" (Pfeffer and Sutton, 2006). This is overcome through consistent interactions and knowledge sharing with the academic community and research institutions (to be aware of the state-of-the-art in the field of interest) and with other companies through seminars, factory visits, or joint problem-solving. Open innovation clearly has implications for SS&OP but is also invaluable to fast-track the overall sustainability agenda into actionable.

Conclusions

This research uncovered an array of technology-driven sustainability initiatives related to SS&OP that the case companies are practicing in contrast to those activities that they have not been able to implement just yet. This gap between practice and the potential opportunities for sustainability that emerge from new digital technologies is explained through the lens of roadblocks caused by a variety of cultural, capability-based, collaborative, and contextual factors. We propose open innovation to be a step forward for viable sustainable solutions, adding to the proposals of Roscoe *et al.* (2020) on involving external stakeholders in the SS&OP process to break out of structural lock-ins and path dependencies in the organization, as well as roadblocks that hinder the ability to prioritize the sustainability objectives. The digitally enabled SS&OP process is to serve as a platform for cross-functional coordination and collaboration with external stakeholders.

Open innovation initiatives involving publicly funded, large-scale R&D consortiums with academic institutions, research centres, and other businesses enable:

- Companies to improve their understanding of the state of the art
- Engage in research from the supply chain perspective, involving primary and secondary stakeholders beyond the organizational boundaries

- Leverage the infrastructure of academic and research organizations for advanced scientific research and methodologies
- Gain exposure to the sustainability initiatives of other organizations
- Practice evidence-based management

Note

1 www.ellenmacarthurfoundation.org.

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Appendix 1

Acronyms

S&OP	Sales and Operations Planning
SS&OP	Sustainable Sales and Operations Planning
R&D Consortiums	Research and Development Consortiums
OEM	Original Equipment Manufacturers
I4.0	Industry 4.0
VoSS	Voice of Secondary Stakeholders
AM	Additive Manufacturing
AR	Augmented Reality

Chapter 7

Materials science and ontologies

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Introduction

Challenges in material innovation towards manufacturing

Materials science is a cornerstone for the development of new manufacturing processes and products. The creation of a new product often starts with materials innovation to improve or replace existing materials. Materials innovation usually includes laboratory experiments, testing, materials characterisation and modelling at various levels of granularity. The research methods in use today have their origins in a wide range of communities, such as chemistry, solid-state physics, materials technology, mechanical engineering, etc. The path from candidate material development to manufacturing of the end product requires multiple consecutive and iterative steps involving multiple fields along the value chain, including additional fields not anchored in materials science, like design, life cycle analysis, safety, sustainability, scale-up and logistics. Each of these fields involves separate communities with their own standards, posing a significant challenge for the exchange of requirements and materials knowledge as well as the efficient use of the information provided.

The key to addressing this challenge lies in interoperability and a robust exchange of knowledge between all stakeholders along the manufacturing path.

Materials digitalisation: the new paradigm

The complexity of the above-mentioned challenge, both in terms of its size and diverse involvement, demands cyber-physical systems and technologies that can support the transition to Industry 5.0 [1] and its focus on greater collaboration and knowledge exchange between humans and machines, involvement of all stakeholders (workers, shareholders, research communities and society) and sustainability. In this chapter, we will focus on materials knowledge and how it can be exchanged between different disciplines involved in the development of new manufacturing products and processes.

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The need to coordinate and integrate different communities and their respective methodologies was recognised within the materials modelling community in Europe, leading to the establishment of the European Materials Modelling Council (EMMC) [2] in 2014. A first significant step towards standards and integration was taken by a commonly agreed-upon terminology and classification for materials modelling [3] and a regularly updated roadmap for materials modelling and digitalisation [4]. The roadmap is aligned with the widely endorsed FAIR principles [5] that were coined in 2016, providing guidelines for making data *Findable*, *Accessible*, *Interoperable* and *Reusable*. A similar undertaking was done for materials characterisation, with the establishment of the European Materials Characterisation Council (EMCC) in 2016 [6], which is now closely interacting with and aligned with EMMC. Another important effort for providing a common semantic basis (a human and machine-interpretable language) for materials science and applied sciences, in general, was the initiation of the Elementary Multiperspective Material Ontology (EMMO) [7, 8] in late 2016. EMMO provides a logically rigorous basis for the description of concepts and terminology within applied sciences and a common ground for deep information exchange between experts and the implementation of semantic interoperability.

In 2021, the Advanced Materials 2030 Initiative [9] was initiated with the Materials 2030 Manifesto [10] and one year later followed up with the Materials 2030 Roadmap [11] on how to address the needs for a strong European ecosystem for materials to drive the green and digital transition. The roadmap highlights materials digitalisation as a key priority for meeting the needs for sustainability and expectations from society. Figure 7.1 shows the four prioritised topics within materials digitalisation for accelerating

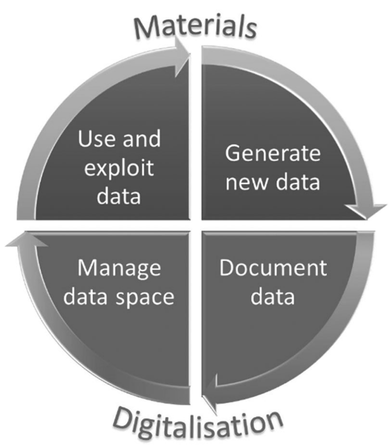

Figure 7.1 The four priority topics to achieve the data life cycle of advanced materials. From Ref. [11].

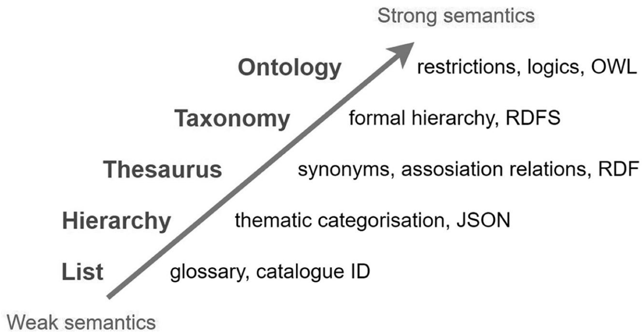

Figure 7.2 Illustration of Semantic Knowledge Organisation (dashed line indicates the limit to enabling semantic interoperability). Adapted from Ref. [12].

the design and use of advanced materials by creating efficient pathways for harvesting and exploiting relevant data. These priorities rely on the efficient exchange of materials knowledge between different stakeholders.

Path towards a solution: semantics and interoperability

Semantic knowledge organisation refers to the organisation of information, providing not only data but also meaning and logic at some level of detail. The level can range from a controlled vocabulary for representing the types of entities in a given domain via a thesaurus and taxonomy (hierarchical classification) to a fully-fledged ontology, as illustrated in Figure 7.2.

We define *compatibility* (from Latin cum = with and pati = to suffer) as the ability of two or more systems to establish a one-to-one connection between them, usually due to strong similarities in their internal representations that facilitate mutual understanding (e.g. for software, this usually happens when systems are parts of a set of tools provided by a common developer) (Figure 7.3b). In a compatibility scenario, systems are fully aware of the type and identity of the other connected systems.

We define *interoperability* (from Latin inter = between and operari = to work) as the ability of two or more systems to exchange information between them through a common representational system to perform a complex task that cannot be done by each single system alone. The presence of a common representational system provides the highest level of generalisation and replaceability and means that no privileged one-to-one connection between two system types should be implemented within the interfaces (Figure 7.3a). In principle, in an interoperability scenario, one system can ignore the details about other systems.

In software systems, compatibility is typically achieved by means of defining and adhering to particular formats or syntaxes; hence, it is also referred to as “syntactic interoperability”. In contrast, interoperability as defined

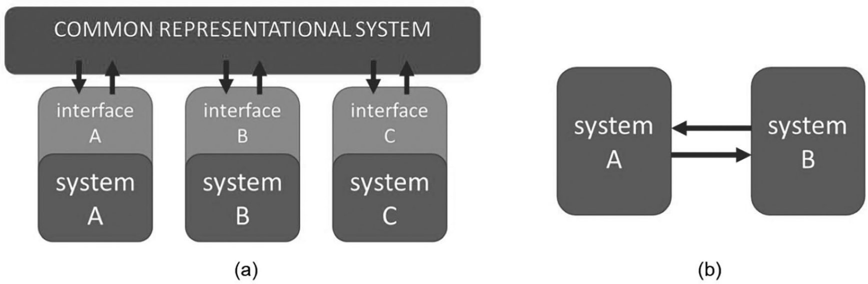

Figure 7.3 Interoperability (a) vs compatibility (b).

above is associated with so-called "semantic interoperability". Most systems today operate at lower levels, i.e., they are compatible due to syntactic interoperability.

At the highest level of abstraction, we find interoperability environments enabling interactions at the human level – between scientific communities or experts belonging to different fields. Such interoperability/integration is achieved by establishing a common "language" (i.e. a common vocabulary, terminology and standardised classification) covering various communities and sub-disciplines that can be used to represent the information. A common language understood by each member of the scientific community will enable effective information exchange.

In Section "An ontology for material science", ontologies are presented in general, including the needs for materials science and a brief introduction to EMMO. Section "Application of ontologies for materials science" shows some applications of ontologies for materials science, starting with the general case of data documentation and followed by some application examples. Finally, Section "Further perspectives" highlights further perspectives.

An ontology for material science

What is an ontology?

An ontology is a formal representation of knowledge that describes the concepts and relationships within a specific domain. Ontologies help to standardise the representation of knowledge within a particular domain and thus facilitate communication and interoperability between different systems and applications. They provide a shared and commonly accepted formalisation of concepts, allowing the knowledge to be understood by experts of different disciplines and by automated systems that can be the basis for artificial intelligence (AI) or big data applications. This can be achieved at different levels of the semantic spectrum using systems that span from lists of terms to complete and decidable logical systems at the ontological level (Figure 7.2).

Ontologies are commonly used in computer science and artificial intelligence applications, such as semantic web technologies and knowledge management systems.

Formally, an ontology consists of classes (representing the concepts), individuals (specific instances of a concept representing a concrete object) and relations (for example, properties) between them, as shown in Figure 7.4a. In addition, can ontologies contain axioms, which are facts or statements that are asserted to be true in the domain being described, as well as rules that define how the classes and properties can be used together. Each class, individual or relation in an ontology is uniquely identified, typically by an Internationalised Resource Identifier (IRI). For example, the IRI http://emmo.info/emmo#EMMO_a4d66059_5dd3_4b90_b4cb_10960559441b uniquely identifies the concept of manufacturing in EMMO. Figure 7.4b shows a simple example of an ontology and how it relates to real-world entities. In this case, the real-world objects are a specific aluminium microstructure and one of its properties, its yield strength, as obtained from a measurement following a given procedure. In the ontological world, individuals

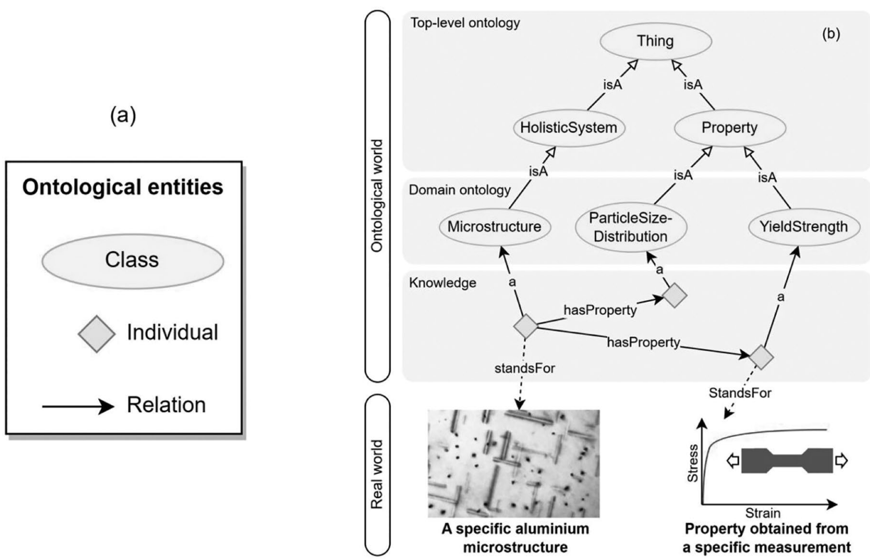

Figure 7.4 (a) ontological entities. (b) an example of an ontology and how it relates to real-world entities. The arrows in (b) have different meanings; the arrows with empty heads represent sub-class relations (rdfs:subClassOf), the arrows labelled "a" relate individuals to the class they belong to (rdf:type) and the two arrows labelled "hasProperty" are relations between individuals. The two dotted arrows relating individuals to the real world entities that they stand for are not part of the ontological world.

stand for real-world objects and the relations between them. The ontology also provides a strong classification of the individuals in terms of well-defined classes. Formal logic is used to (axiomatically) describe whether an individual of one class also is or cannot be an individual of another class, making it possible to both express complex class dependencies and infer new knowledge from the ontology. Figure 7.4b also illustrates that an ontological system is typically divided into different levels – here simplified to a top, domain and knowledge level. The term ontology is typically used for a consistent set of classes (and axioms) in a given domain. When speaking about the entire ontological representation, including the individuals representing a given use case, the terms *knowledge base* or *knowledge graph* are typically used.

The case of materials modelling

The great diversity of terminology and descriptions of materials modelling has been one of the fundamental challenges in establishing a coherent knowledge representation. A solution emerged as a result of a cataloguing and careful analysis of modelling used in more than one hundred European projects, published in the Review of Materials Modelling (RoMM) [13]. It turned out to be possible to categorise models by four different "entities" (see Figure 7.5).

Materials modelling accordingly involves choosing the level of granularity to describe the material and does this in terms of the behaviour of a set of entities.

It follows that any material can be described by any of the entity types. Also, the scale of the material to be described is, in principle, separate from the entity and its granularity. A manufactured object can be modelled at the granularity of for example components or microstructure.

Having chosen the entity (and hence granularity), the materials model involves a "physics equation", which is based on a fundamental physics

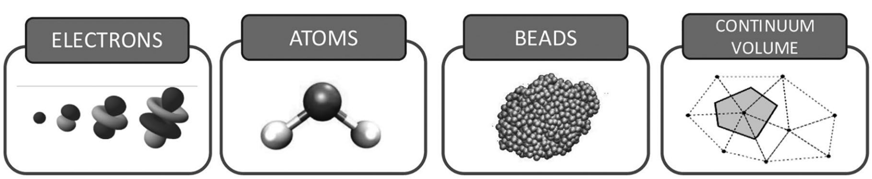

Figure 7.5 Materials model entities: self-contained, internally frozen, structure-less representational units of a material. Standard definitions of electron and atom apply. Bead: a mesoscopic entity consisting of more than one atom (e.g. nanoparticles, grains). Continuum volume entity: a representation of the material bounded in a region of space within which the material is considered to be described by the same set of properties. Originally published in Ref. [8].

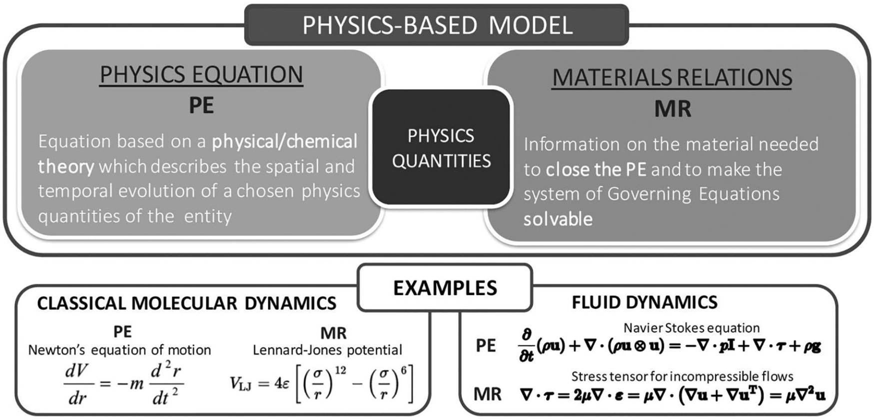

Figure 7.6 A physics-based materials model consists of a physics equation describing the behaviour of an entity and materials relations to make a solvable set of equations. Figure from Ref. [8], which presents the classification work done by Anne F de Baas in the RoMM [13].

theory and defines the relations between the physics quantities of an entity. Well-known examples are Newton's equations, Navier-Stokes equations and the Schrödinger equation. To solve the physics equation, materials-specific equations providing values for parameters in the physics equation are needed. Together with the physics equation, these "materials relations" form a complete set of equations that is solvable, as shown in Figure 7.6.

This classification leads to a great simplification across the wide field of materials modelling. All physics-based models can be categorised by the four entities. For each of the entities, there are about six different physics equations. Of course, much of the knowledge about the specific material is represented in many different materials relations. In atomistic modelling, these are the different potential functions and "forcefields" describing interactions. In continuum mechanics models, materials relations are in fact often referred to as the "materials model". Note that the computational representation of the materials model should be kept entirely separate from the model itself; e.g., finite elements are often used for computational representations of continuum mechanics models. Models are hence classified by their entities (granularity), physics equation and materials relation, neither by the scale of application nor by the computational representation.

The terminology and rigorous classification of materials modelling conducted by EMMC as a CEN Workshop Agreement (CWA) [3] led to a relatively small number of distinct materials models, replacing the former situation of opacity of materials models and simulations that made the field hard to access for outsiders. It also provided a systematic description and documentation of simulations, including the user case, model, solver and post-processor: the "materials MOdelling DAta" (MODA) [3]. It organises information so that even complex simulation workflows can be conveyed more easily, and key data about the models, solvers and post-processors and their implementation can be captured consistently and transparently.

The Elementary Multiperspective Material Ontology (EMMO)

In order to formalise the domain knowledge in materials science, in particular, in an ontology, it is important to have a foundational ontology based on core concepts and perspectives of applied sciences.

These include the scientific view of the world; in particular, there are few "absolutes", e.g., the existence of a universe, and there are basic "rules" that apply everywhere. Patterns and behaviours driven by these rules are uncovered by observation. The latter leads to understanding on a subjective level but not to absolute truths. Similar investigations can lead to different results and have different interpretations. There are accepted scientific laws, for example, regarding elementary entities and their interactions (standard model), cause and effect, conservation of quantities and the fact that matter (fermions) and fields (bosons) are fundamental families of physical entities. An ontology for materials sciences needs to have a straightforward representation of these as well as our understanding of materials in terms of abstract representations of materials structure and the ability to apply granular partitioning into a multitude of separately definable and interconnected levels of size (e.g., micro, meso or macro level items). Furthermore, the close coupling of processes, structure and properties, as well as the need to be able to deal with quantum systems, demands that the spatial and temporal aspects are not separated.

The motivation for creating EMMO as a new foundational ontology for materials stems from the fact that existing ontologies only partially cover the above desiderata. The scope and objectives of EMMO can hence be summarised as follows:

- Common representational framework deeply based in physics, chemistry and materials science.
- Consistent with fundamental theories.
- Ability to represent all materials, chemicals and physical phenomena in a consistent manner.
- Ability to capture all scales and levels of description and zoom in and out in a "hierarchical" manner.
- Capture the strong interrelation between "real world" physical things and their observations/characterisation as well as modelling.
- Ability to deal naturally with changes and processes.

The theoretical foundations of EMMO include:

- **Mereocausality**: A new first-order logic (FOL) theory developed specifically as a foundation for EMMO [14]. It combines classical mereology, the science of parthood relations (part to part and part to whole) with causality (cause and effect). It provides an applied sciences-friendly framework for the representation of spatio-temporal relations among entities. In fact, space and time are not axiomatically assumed in EMMO but rather follow from this underlying theory.
- **Set theory**: The theory of membership. EMMO has a set class representing the collection of all individuals (signs) that represents a collection of items. EMMO makes a strong distinction between membership and parthood relations. In contrast to sets, items can only have parts that are themselves items. For further information, see [15].
- **Semiotics**: The study of meaning-making. It is the discipline of formulating something that possibly exists in a defined space and time in the real world and is used in EMMO to reduce the complexity of a physical thing to a simple sign (symbol) based on Peirce's semiotics [16, 17].
- **Topology**: the study of geometrical properties and spatial (and timewise) relations.

The name *EMMO* should be understood as follows: *elementary* means that EMMO is a discrete ontology, assuming the existence of the smallest possible part; *multiperspective* highlights an important aspect of EMMO – that it is possible to describe the world from different perspectives; *material* (as the opposite of immaterial) emphasises that EMMO is strictly nominalistic, meaning that it assumes that abstracts do not exist. Material also refers to the historical scope of EMMO, aiming at the description of materials and thus covering the needs of physicists and applied scientists.

EMMO development provides a multi-level formalisation of the ontology (i.e. from simple taxonomy to OWL or FOL) in order to be the base for AI applications and data harvesting and interpretations (industry commons and BigData). As shown in Figure 7.7, EMMO is structured hierarchically into

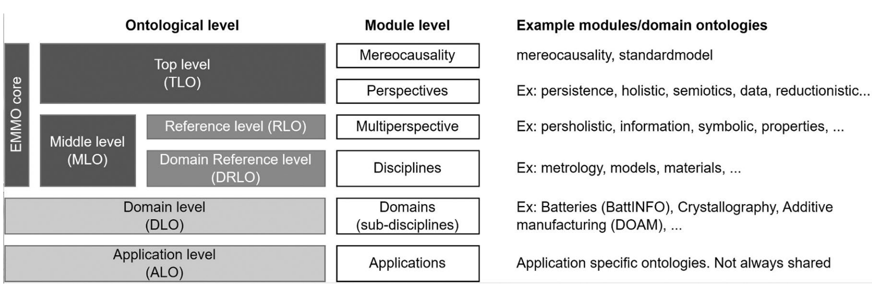

Figure 7.7 The hierarchical structure of ontological levels of EMMO and its domain and application ontologies.

four levels: mereocausality and perspectives at the top level and multiperspective and disciplines at the middle level. Below these, there is a hierarchy of domain- and application-level ontologies.

A full account of EMMO is the subject of a forthcoming publication. Here is just a short outline of the four levels.

Mereocausality level

The fundamental mereocausality theory, where everything is defined (no primitive concepts) according to the causal network between entities whose types and interactions are governed by the standard model and quantum field theory, 4D spacetime arises as a consequence of the combination of mereological fusions and the topological structure of the causal network. The purpose of this level is to provide a consistent theoretical framework anchored in modern physics, providing an unambiguous representation of the world. Users of EMMO can benefit from this foundation without having to learn the underlying theory.

Perspective level

A key feature of EMMO is its ability to represent the world from different perspectives. This is a novel and essential feature for an ontology that has the ambition to express the domain knowledge of all fields of applied sciences. Currently, EMMO includes seven perspectives, as shown in Figure 7.8, but it is possible for users to define their own:

- **Perceptual**: Considers the world as perceived according to human perception mechanisms (visual, auditory, somatosensory, gustatory or olfactory).
- **Physicalistic**: Categorises physical objects only by concepts coming from applied physical sciences.
- **Persistence**: Categorises 4D world objects as they extend in time (process) or as they persist in time (object).
- **Holistic**: Considers each part of the whole as equally important, without the need of a granularity hierarchy (in time or space).
- **Semiotic**: Describes a triadic process in which an interpreter provides a sign for a real-world object. This perspective is based on Peirce semiotics [16] and is about providing meaning. It can be applied to describe processes such as:
  - Measuring the same sample with different devices
  - Providing physical quantities via experiment or modelling
  - Registering feedback from different user experiences
  - Representing different theories for the same phenomenon
  - Applying different names to the same object

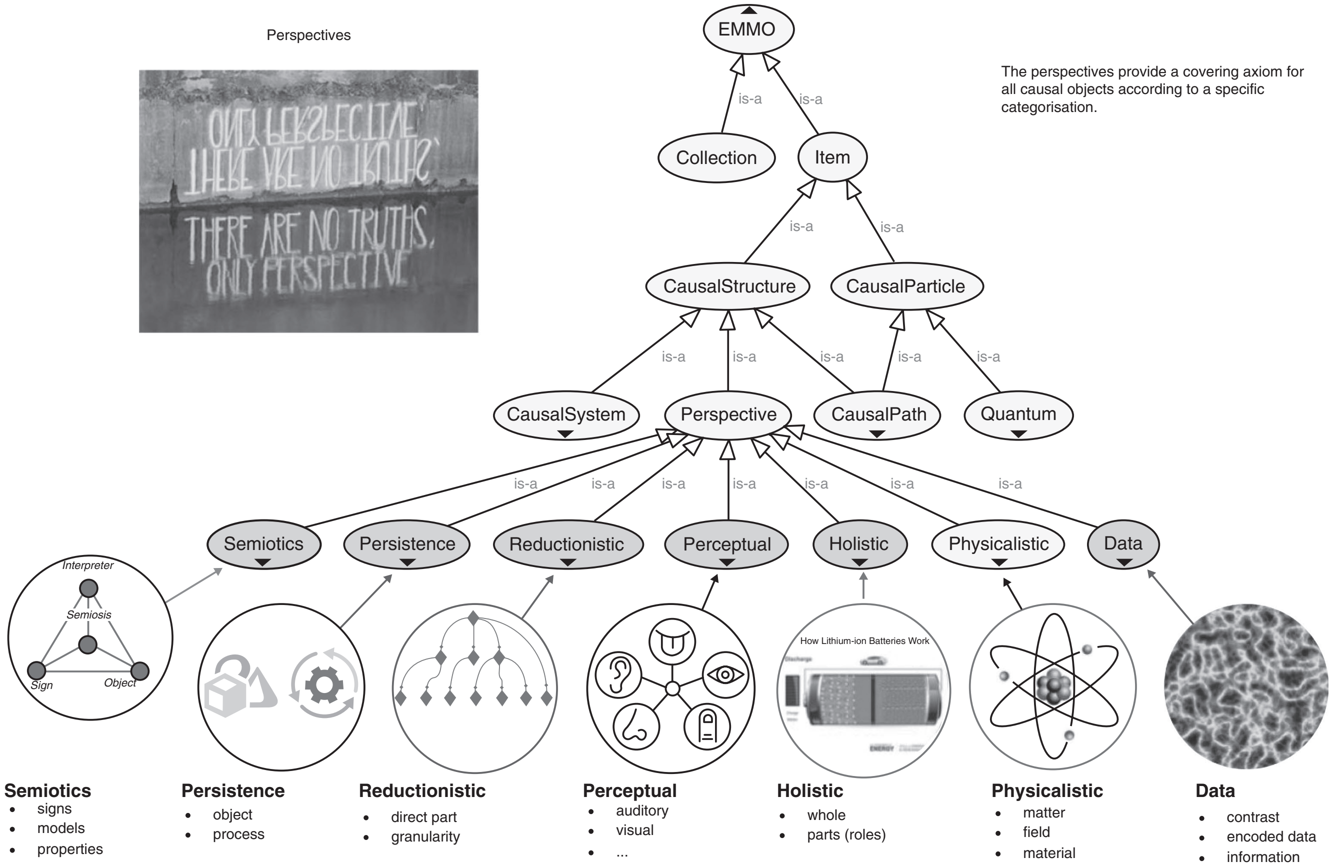

Figure 7.8 The different perspectives currently defined in EMMO.

    - Separating what is expected to be (e.g. blueprint) to what will be (e.g. the building)

- **Data**: Categorise data as physical patterns, or gradients, according to their characteristics independently from the carried meaning following the description of information by Luciano Floridi [18].
- **Reductionistic:** Categorises objects according to their granularity relations. This perspective provides the novel notion of direct parthood, allowing a univocal description of granularity levels.

Multiperspective level

Concepts that can be introduced by merging more than one perspective, introducing or not a further level of subjectivity, An example is *information* (usually defined as "data with meaning"), which is the combination of the *data* and *semiotics* perspectives.

Discipline level

The modules at the discipline level provide fundamental concepts limited to specific disciplines. Materials, models and math are examples of disciplines. These are used within many domains and are essential for achieving cross-domain interoperability.

Materials Science ontologies

The motivation for creating an overarching framework for applied sciences is motivated by the heterogeneous nature of the field as well as the strong growth of the field, which calls for some level of harmonisation. A review by Zhang et al. [27] included nine materials ontologies, whereas a more recent study by the OntoCommons project already includes 29 [19]. In addition, there are a number of ontologies in the domain of chemistry [20, 28]. EMMO is able to address the needs for a semantic description that covers the wide physical sciences integration requirements of materials modelling.

Application of ontologies for materials science

Figure 7.9 illustrates the key aspects of the flow of data and knowledge from its generation, documentation, management and final exploitation as identified in the AMI2030 roadmap [11]. Ontologies play an important role for all these steps. Due to the limited scope, we will here only focus on data documentation and examples of industrial manufacturing cases using ontologies for data exploitation.

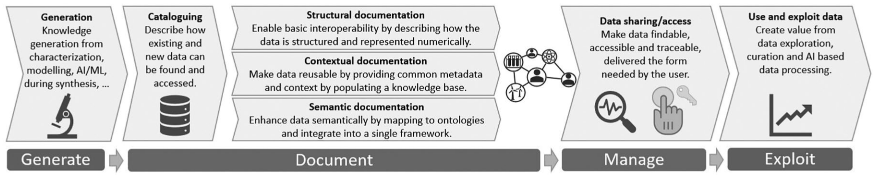

Figure 7.9 The flow of data from generation to exploitation and value creation. The labels at the bottom refer to the four priority topics in the AMI2030 roadmap, as illustrated in Figure 7.1. While cataloguing is an essential step for making data available for management and exploitation, is it possible to include or omit each of the three higher levels of data documentation.

Data documentation

Data documentation is the process of recording all relevant aspects of data to make it FAIR and facilitate its use and exploitation. Data can be documented at four distinct but interconnected levels:

Cataloguing provides a standardised way of describing and indexing data resources, making them easier for users to locate and utilise. It should provide sufficient information about where the data is located, the protocols used to access the data, the needed authentication and authorisation procedures, etc. to make it accessible. In addition, data catalogues also include standardised metadata, such as title, keywords, license, owner, project, contact person, format, etc., enabling a basic keyword-based search.

Structural data documentation describes how data is structured and represented numerically. It is an essential step for going from compatibility to interoperability. By standardising the description of the data representation, it becomes easier to combine and integrate data from various sources and make it more easily accessible to a broader range of users. The Datamodel Ontology [21] provides a standardised representation for data models that can help to ensure interoperability across different applications and contexts. This ontology is a simple yet comprehensive representation of the data, designed to be feature complete and easy to use. SFI Manufacturing has contributed to the development of DLite [22], which is a concrete implementation of an interoperability framework that uses the Datamodel Ontology.

Contextual data documentation is about providing sufficient context for the data to make it reusable. This is typically done by relating or linking the data items to other data items (aka *linked data*) in a knowledge base. For example, consider a dataset consisting of results from tensile tests from a series of welded joints between aluminium and steel. The obvious context that would be needed for most reuse of this dataset is the geometry of the welded sample, from where the sample is taken, how it is loaded, the composition and temper of the aluminium, steel and filler materials, type of welding and welding parameters such as temperature and welding speed. Additional useful context to this dataset would, e.g., be references to related datasets for the same sample, like TEM characterisation of the intermetallic phases that formed at different distances from the centre of the welding zone. Other metadata, like who performed the tests, when and in what project, is useful for search and data exploration. All such metadata can be expressed with RDF subject-predicate-object triples (each identified with an IRI)[1] in a knowledge base, resulting in a rich graph of linked data. In addition to reusability, contextual documentation also enables data exploration and semantic search.

Semantic data documentation expresses the shared meaning of the data by mapping it to concepts in published ontologies that are uniquely identified with IRIs. The logical structure of ontologies enhances the contextual data documentation by allowing the user to infer new relations between data items, as shown in the examples in Section "Application examples". Semantic data documentation enables the unambiguous exchange of knowledge and, thereby, cross-disciplinary and semantic interoperability. It also allows for advanced data exploration by exploiting the logical structure of the underlying ontologies.

Today, many data documentation systems only include cataloguing, limiting the use of their data to compatible systems, or requiring significant human intervention and effort to use their data. To increase the level of FAIRness and address the need for cross-disciplinarity and semantic interoperability, all levels of data documentation are required, supported by an ecosystem of ontologies and semantic tools.

Application examples

In this section, we will briefly describe two examples of how ontologies can be used for data exploitation in two real materials-related manufacturing cases originating from the OntoTrans [23] and OpenModel [24] EU projects.

Production of steel beam

Innovation: Energy-efficient, lightweight, and sustainable production of hot-rolled steel H-beams (Figure 7.10a), while meeting the demanding requirements on mechanical properties [25].

Challenge: To master the relationship between process parameters and the materials properties of the hot-rolled H-beams. Currently, process parameters and materials properties are managed via testing procedures, which use up significant time and resources and generate large sets of data.

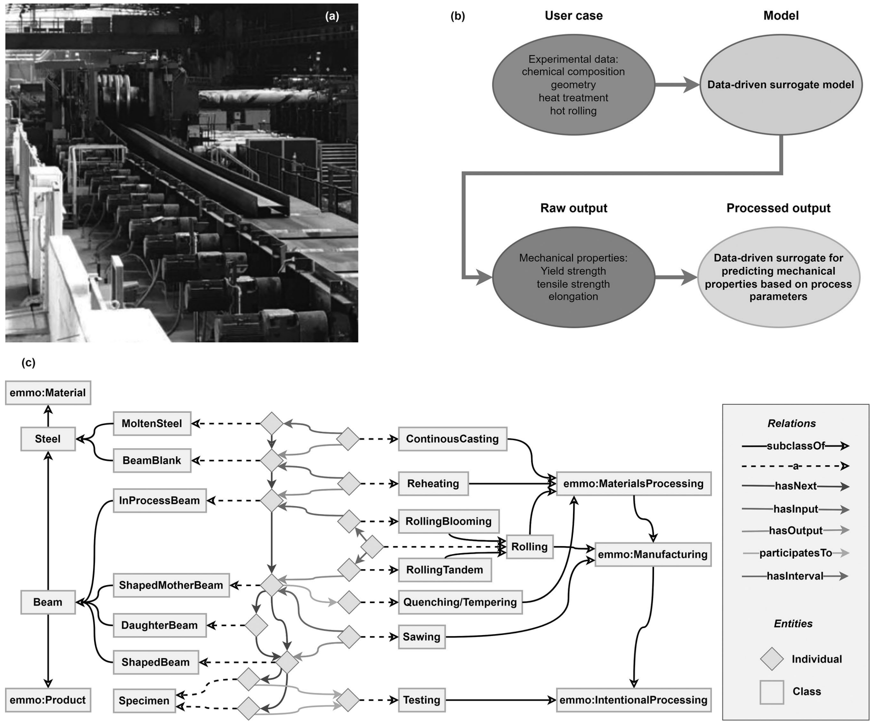

Figure 7.10 H-beams production line (a), modelling workflow (b) and semantic description (c)

Solution/Approach:

- Identify and define all the steps in the section mill steel beam manufacturing process (Figure 7.10b).
- Semantically document the case by ontologising the description of the underlying manufacturing processes (Figure 7.10c).
- Create data models for structural data documentation to exchange the data between the different tools.
- Create a surrogate model of the underlying system to allow efficient multi-objective optimisation (MOO).
- Perform MOO on the surrogate model to identify the Pareto optima cases, utilising the data models for interoperability.

Benefits semantic data documentation:

- More systematic description of the parameters and inter-relations.
- Connect the measured data to more generic concepts.

- The analysis is not dependent on the specific format provided by the plant; retrofitting or upgrading of the sensors or models is greatly facilitated.

Corrosion of aluminium-reinforced concrete

Innovation: Development of a new sustainable concrete mix tailored for aluminium reinforcement (less alkaline to avoid corrosion), with less energy intensive production, a significant reduction of CO_2 emissions, allowing slimmer lightweight concrete structures and a longer lifespan (leading to less waste) [26]. Figure 7.11a shows an aluminium-reinforced bench created for demonstration purposes.

Challenge: To predict and control the formation of the protective layer at the interface between the concrete and the aluminium reinforcement and to assess the resistance to corrosion under the load of the reinforced concrete. The analysis requires complex interactions between chemical reactions, aluminium microstructure, external loading, corrosion and the microlayer at the aluminium interface (Figure 7.11b).

Solution/Approach:

- Identify and define a modelling workflow to efficiently predict the protective layer behaviour (Figure 7.11c).
- Build an ontology to describe the material and the workflow (Figure 7.11d).
- Document the modelling tools, including their input and output, semantically.
- Utilise the OpenModel Open Innovation Platform to execute the workflow while optimising geometries and process parameters.

Benefits of semantic data documentation:

- Focus on the physics and concepts, abstracting away details about the underlying data format and representations.
- The semantic description of the models and workflow allows for model interchangeability (for example, replace Abaqus by Ansys).
- Facilitate the integration of experimental results for calibration and validation while relying on a common language.

Further perspectives

A standardised terminology will improve future exchanges among experts in the entire area of materials characterisation and modelling. It will facilitate the exchange with industrial end-users and researchers and reduce the barrier to utilise materials modelling. The common language is expected to foster dialogue and mutual understanding between industrial end-users,

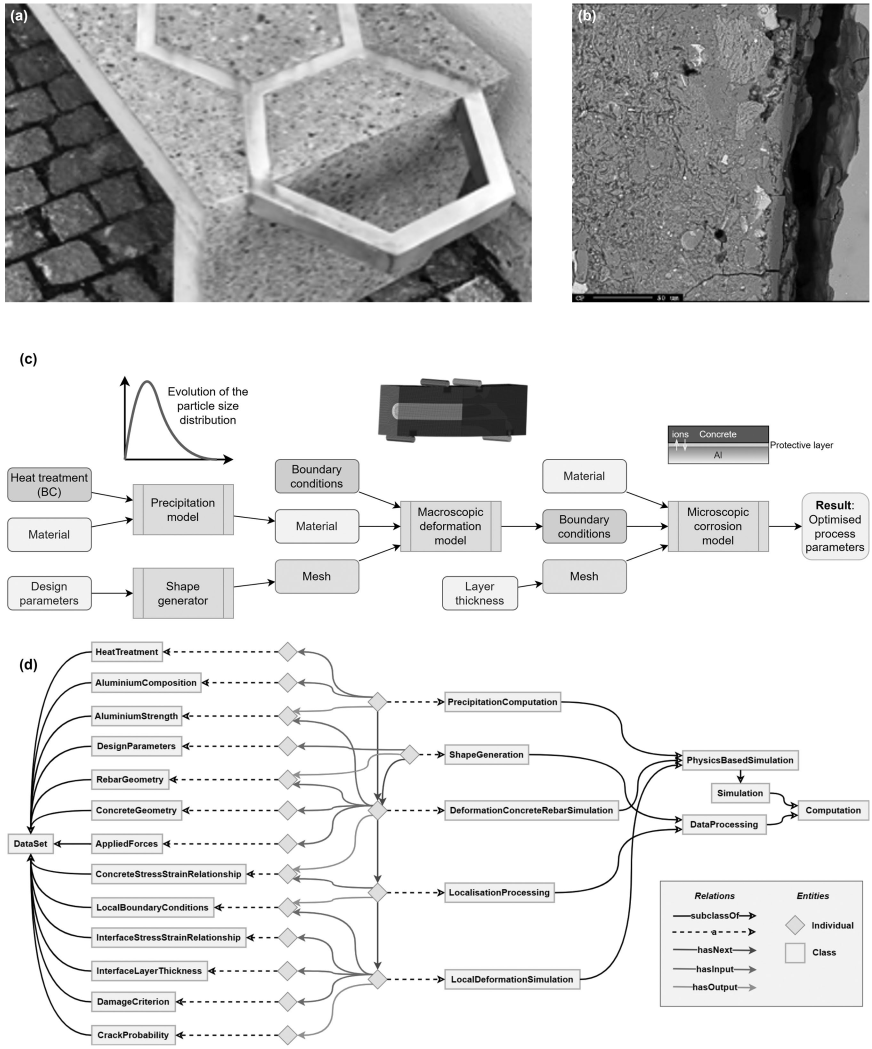

Figure 7.11 Aluminium-reinforced concrete and protective layer. (a) Demonstrator of an aluminium-reinforced concrete bench; (b) microstructure at the interface at the concrete-aluminium interface; (c) modelling workflow; (d) semantic description of the modelling workflow.

software developers, scientists, and theoreticians. It also constitutes the first step towards interoperability.

The development of EMMO is relevant for an integrated technological development and brings benefits for industrial end-users in terms of common understanding and improved communication, knowledge management, cross-discipline and semantic interoperability, consistent data interpretation and linking of resources, advanced search and data exploration, inferencing and reasoning and providing answers to queries that would otherwise remain unanswered. It will facilitate the digitalisation of materials and manufacturing and enable powerful AI applications.

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Note

1 Except for objects, which may also be a literal value.

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Chapter 8

Towards semantic standard and process ontology for additive manufacturing

Sylvain Gouttebroze, Jesper Friis, Even Wilberg Hovig, and Klas Boivie

Introduction

Additive manufacturing (AM) is becoming a reliable manufacturing route due to the improvement of equipment, procedures, and feedstock. Normally, a manufacturing process chain based on AM requires a series of operations and sub-processes in addition to the actual AM process. Preparations and post-processing operations can have a critical influence on the properties of the final product and therefore, combining multiple models across various scales and accounting for multiple physical phenomena is necessary. This modern production method requires a high level of automation and the integration of models and simulations for designing the part, configuring, and automating the process, and predicting the performance. In industrial applications, processes like laser-based powder bed fusion (PBF-LB) not only demand considerable production time but also rely on high-quality feedstock material, which can be quite expensive. A failure during production, or producing a flawed product, significantly impacts the overall production costs. This is especially true for customised or small-series manufacturing, a common application of AM. Establishing reliable procedures and gathering expert knowledge has been a major focus of the last decade's work. There's a pressing need to link component properties with process choices. These choices include support structures (both internal and external), slicing, orientation, laser path, and laser parameters. This connection has spurred numerous research studies and the development of numerical models. This knowledge and practical experience must be spread and reused to facilitate the industrial application of AM. Ideally, this knowledge can be formalised and stored in a knowledge graph. This step is crucial for implementing smart manufacturing. The next generation of manufacturing systems will possess cognitive capabilities. They'll control task execution based on sensor measurements, using reasoning derived from existing formal knowledge. The development of dedicated ontologies for material, process, and product is essential to convert existing knowledge into machine-readable, logical relations.

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By definition, international standards may contain product performance requirements, describe recommended or required best practice testing procedures, or specify the content of services and the methods by which they should be delivered. They can also include terminology. The aim of standards is to provide clear guidelines for consistent function and quality and to improve processes, enhance transparency, and facilitate comparison. Clarity in communication is critical. Clarity in communication is critical. Thus, the use of vocabulary, including terms and their definitions, should remain consistent and coherent across all standards addressing a given topic. This requires that a terminology standard is developed and widely accepted by consensus in the community. The development of international and industrial standards is mostly conducted through dedicated standard development organisations (SDOs) such as ISO, CEN/CENELEC, ASTM International, ASME, and other national or industry association-driven organisations, as presented in Kawalkar *et al.* [1].

On the other hand, an ontology represents knowledge as a map or graph of concepts within a domain and their relationships. Ontologies are commonly expressed as annotated, machine-readable knowledge graphs. Ontologies assign meaning to data such as measurements, procedure descriptions, and models. They also provide links between data and enable machine reasoning. In various domains, ontologies have demonstrated their value as tools for addressing knowledge and interaction challenges. Still, in the manufacturing domain, ontologies are at an early development stage. Sanfilippo *et al.* [2] compared various ontologies and introduced a new one rooted in DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering) [3]. In this study, we relate the ontology to the EMMO [4]: "The Elementary Multiperspective Material Ontology (EMMO) is the result of a multidisciplinary effort within the European Material Modelling Council (EMMC), aimed at the development of a standard representational ontology framework based on current materials modelling and characterisation knowledge". The development of EMMO is rooted in modern physics and material sciences, endorsing the view that the world can be described from fundamental causal interactions between "quantum" objects. A benefit of EMMO, in the scope of this study, is its intrinsic link to material and process modelling.

The present work addresses AM technology and will therefore focus on extracting information only from the international standard for terminology in AM technology, ISO/ASTM 52900 [5]. To build an ontology based on a published standard, we need to parse the text to extract terms and definitions and further categorise the content. Our goal is to create a semi-automated method for building an ontology using the online HTML version of the published terms and definitions. Subsequently, the ontology is integrated with existing top-level and domain-specific ontologies for a more comprehensive description. The significance and advantages of interoperability are detailed in the third section.

Standardisation and ontologies

The terms and definitions of ISO/ASTM 52900:2021 are accessible through ISO's online browsing platform [5]. The information is presented in a structured HTML document, allowing partial automation of processing using the document's id and class attributes. Automation is crucial for applying the same methodology to other standards in the future and for updating the ontology based on forthcoming document revisions. The main structure is presented in Figure 8.1. The terms are divided into three categories: general, processing, and parts. These sections consist of terms needed to describe key concepts, but they do not represent taxonomical relations. For example, the term "3.12.4 final inspection" is a process and therefore not a subclass of the term "3.9.1 part", while "3.10.1 prototype" could be considered a subclass of "3.9.1 part". The initial step in parsing the HTML document involves extracting the section structure and, concurrently, the grammatical information (as seen in Figure 8.2, the grammatical type is indicated).

The definition of a term often includes references to other terms, as illustrated in Figure 8.2. The procedure for generating the ontology omits language analysis; thus, it won't extract the exact relation type between the terms or the constraints. This data must be manually added later. Currently, as illustrated in Figure 8.3, the procedure creates an ontology class containing the definition, an ID, a section number, and a list of terms referenced in the definition. For each term, the section number is used to add a reference expressed by the *skos:preLabel*. In the absence of defined relations, this information is kept as an annotation to the class. Please note that, as a convention, we will write ontology classes in *italic* in the subsequent sections.

3.1.2
additive manufacturing,noun
AM
process of joining materials to make parts (3.9.1) from 3D model data, usually layer (3.3.7) upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies

Note 1 to entry: Historical terms include: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication and freeform fabrication.

Note 2 to entry: The meaning of "additive-", "subtractive-" and "formative-" manufacturing methodologies is further discussed in Annex B.

Figure 8.1 The topical categorisation of the ISO/ASTM 52900:2021 terms and definitions. Based on Ref. [5].

3.1.4
AM machine,noun
section of the additive manufacturing system (3.1.3) including hardware, machine control software, required set-up software and peripheral accessories necessary to complete a build cycle (3.3.8) for producing parts (3.9.1)

Figure 8.2 The definition of the term "AM machine" in the ISO/ASTM 52900:2021 standard. The text is taken from Ref. [5].

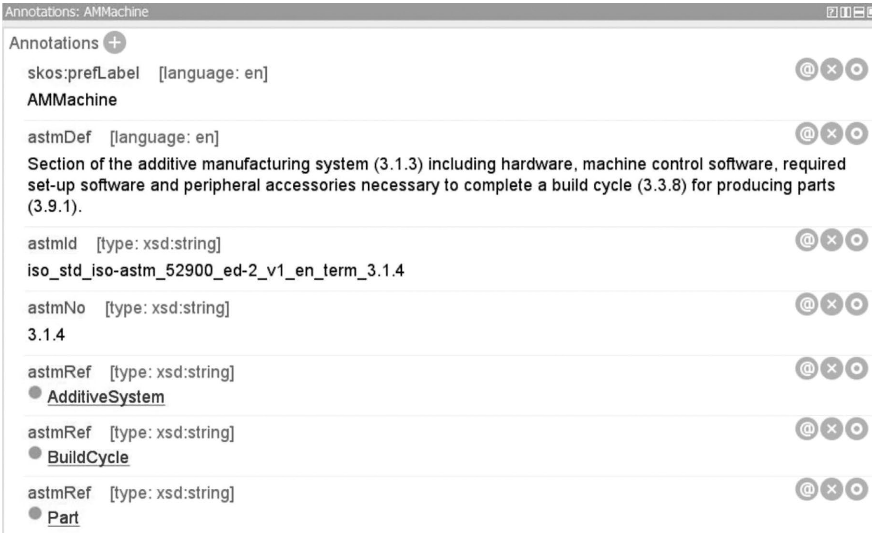

Figure 8.3 Ontologised definition of AM Machine.

After that processing, the ontology structure reflects the grammatical information (*GrammaticalCategorisation*) and the paragraph structure (*ThematicCategorisation*). The next step is to categorise the concepts using higher-level "bridge concepts" (as defined in OntoCommons).[1] Ideally, these higher-level concepts are not novel; instead, they should be related to previously established ontologies. We have defined seven categories, as presented in Figure 8.4.

All previously parsed concepts are manually defined as either a subclass of these categories or a subclass of an existing class. For example, *Pellets* is defined as a subclass of *Feedstock*, which in turn is a subclass of *Material*. These categories represent different perspectives to describe the real world.

For instance, a laser is a piece of equipment that has the role, providing energy to melt the powder. However, it's also made of various materials with specific chemical compositions and can be described as an assembly of various components, each having spatial positions and parthood relations.

This has been formalised in the *Perspective* class in EMMO. For example, *Role* is a subclass of *Holistic* perspective defined where each part of the whole domain is considered equally important. Their spatial location is not relevant, as the focus is on their respective contributions (i.e., their roles). Similarly, a *Process* is seen in the *Persistence* perspective. A 4D object is considered through the process (extend in time) with both a spatial and temporal evolution. From our example, the process could be the melting of the powder, which includes a state change from solid to liquid to solid and a shape change from powder to bulk. It is important to remember that the object or process can be seen from different perspectives depending on the study to perform.

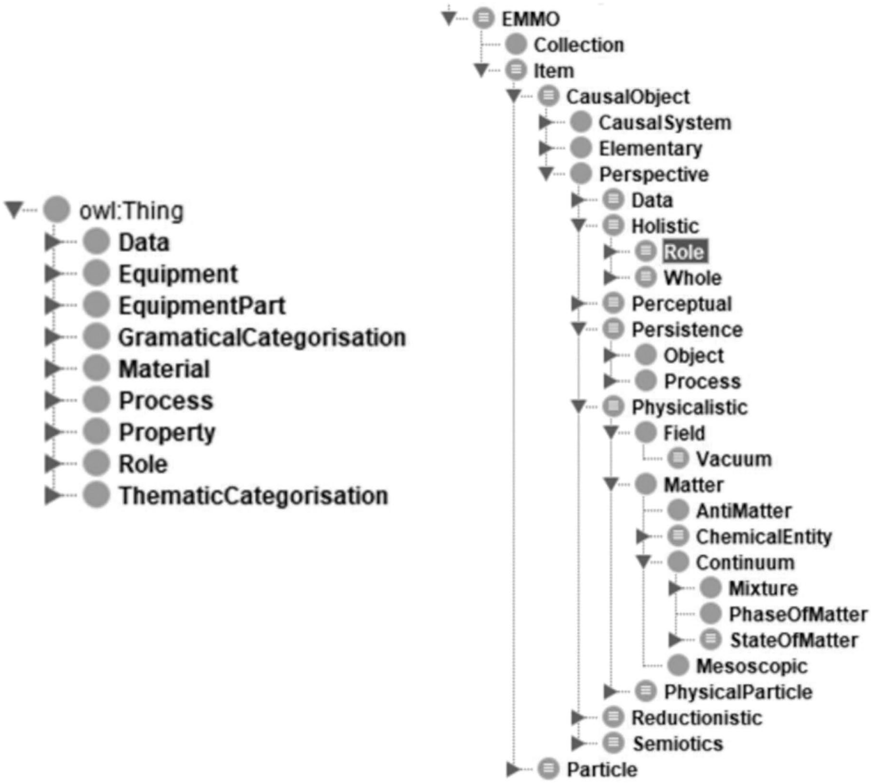

Figure 8.4 Main classes for the domain ontology for additive manufacturing (left) and the top ontology EMMO (right).

The relation between the ISO/ASTM classes and the EMMO classes is important to harmonise the development and facilitate the extension of capabilities. As illustrated in Figure 8.4, EMMO is still very generic, but domain ontologies have been built based on that logical representation. In the application section, we will observe that some information used to describe an AM study falls outside the ASTM standard's scope. Consequently, it's not included in the domain ontology derived from it, necessitating the addition of terms from a microstructure domain ontology.

Data and interoperability

Interoperability is the ability of two or more systems to exchange information between them through a *common representational system* to perform a complex work that cannot be done by each single system alone. A common representational system allows for a high degree of generalisation

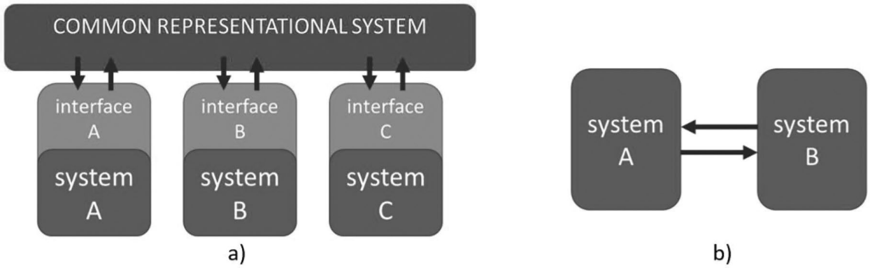

Figure 8.5 Interoperability (a) vs compatibility (b).

and replaceability, eliminating the need for specific one-to-one connections between different system types in their interfaces. In principle, in an interoperability scenario, one system can ignore the details about other systems. Figure 8.5 illustrates the difference between interoperability and compatibility. C*ompatibility* is the ability of two or more systems to establish a one-to-one connection between them, which is usually due to strong similarities in their internal representations that facilitate mutual understanding (e.g. for software, this usually happens when systems are parts of a set of tools provided by a common developer) (Figure 8.5b). In a compatibility scenario, systems are fully aware of the type and identity of the other connected systems.

Interoperability can exist at various semantic levels, including the scientific community level, use case level, and numerical level. To support interoperability between experts from different scientific communities and different digital systems/simulation tools, the common representational system language must be understandable by both humans and machines. The ontological framework described in the previous section serves this exact purpose: to act as a common representational system interpretable by both humans and machines.

Various approaches exist for utilising ontologies on interoperability platforms. The SimPhoNy Open Simulation Platform[2] achieves interoperability by creating a representation using a set of connected classes in the Python programming language. This allows the user of SimPhoNy to seamlessly connect simulation engines, databases, and data repositories. However, for this approach to be effective, a comprehensive ontological description of the use case must first exist.

In the interoperability framework discussed in this work, our primary focus is on the user and ensuring easy onboarding. The starting point is separation of concerns. Figure 8.6 shows an interoperability case where data from a database is used as input to a model. The database and model were developed completely independent of each other. While the database provider is familiar with the structure of the database, they are not experts in ontologies. Like the data provider, the modeller knows what input the modelling tool expects but is unfamiliar with the details of the ontology. Rather than requiring these individuals to detail the data they provide or expect, they're asked to represent their data using simple yet formalised data models, whose structures can closely resemble the database or model input. This approach simplifies the task for data providers, modellers, and potentially external software engineers. They can then easily write drivers to either populate data model A from the database or serialise an instance of data model B into a format the modelling tool expects. By mapping the properties of these data models to shared concepts in the ontology, it is now possible for the interoperability system to correctly create the input to the model from data stored in the database. Only the ontologist needs to understand the intricate details of the ontology and the conversion of properties between concepts. The low-level implementation of drivers for the database or modelling tool can be done by a software engineer. The ontologist can also help add new concepts to the ontology as required by the domain experts.

A semantic interoperability framework based on the principles described above has been developed in a range of EMMC-related EU projects, especially OntoTrans[3] and OpenModel.[4] The main component of this framework is OTEAPI[5] (Open Translation Environment Application Programming Interface), which allows to document different data sources or data sinks in terms of reusable, so-called partial pipelines that can be stored in a knowledge base.

A pipeline, like the one shown in Figure 8.6, can easily be created by connecting a partial pipeline for a data source with another partial pipeline

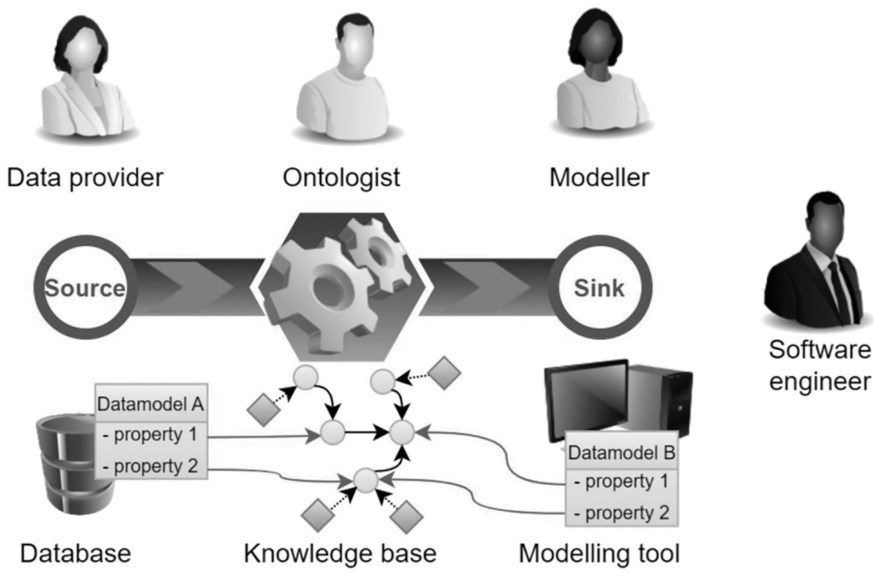

Figure 8.6 Achieving interoperability by separation of concerns.

Source: Created by Jesper Friis with draw.io.

for a data sink. This gives the user a high degree of freedom to mix and match data sources and modelling tools in a very flexible way. It is also possible to combine the pipelines into complex modelling workflows. Other important components of this semantic interoperability framework include the ontology, DLite[6] (an interoperability framework based on data models), and Tripper[7] (a package that provides a common interface to the ontology regardless of how it is stored).

Application

The AM domain ontology[8] based on the ISO/ASTM 52900 standard can be applied to describe current research work on AM. As an illustration, we have selected three papers previously published by colleagues from SINTEF and NTNU (Norwegian University of Science and Technology) with slightly different perspectives. The first paper [6] focuses on process development and improvement. The AM description takes up a significant part of the introduction section and the section on Materials and Methods. The second paper [7] is an intermediate paper linking the process to the properties. The focus on the AM process is smaller and seen more through the sample used for mechanical analysis. Finally, the third paper [8] focuses on the properties of the material produced with AM. The paragraph describing AM process parameters is even shorter, and the second section is named only "Methods" (instead of "Materials and Methods". This difference in section naming reflects the variations in the authors' intentions. For all papers, the interpretation of the results also includes references to AM terminology.

This case illustrates the importance of common terminology and domain ontology, as for all of them, the description of the process should be understandable by all the actors to allow reproducible research. We will now attempt to manually convert the natural language description of the AM process into a semantic description based on our new ontology. In the future, large language models could be applied to automatise this step. We will not completely cover all the data sets, as it might require additional developments in the ontology and other application ontologies. Still, we will try to illustrate the necessary connection to other ontologies in the second section.

Process and equipment

These studies focus solely on PBF-LB as the manufacturing process. The domain ontology includes the term *PowderBedFusion* (see Figure 8.7). This term refers to both *AdditiveManufacturing* and *PowderBed*. This implies that it represents a manufacturing process, an inference drawn from its relations. Additionally, it is applied to a material initially viewed as a geometrical domain, as depicted in Figure 8.8. This example also shows that the ontology, when extracted from the standard using the current methodology, is

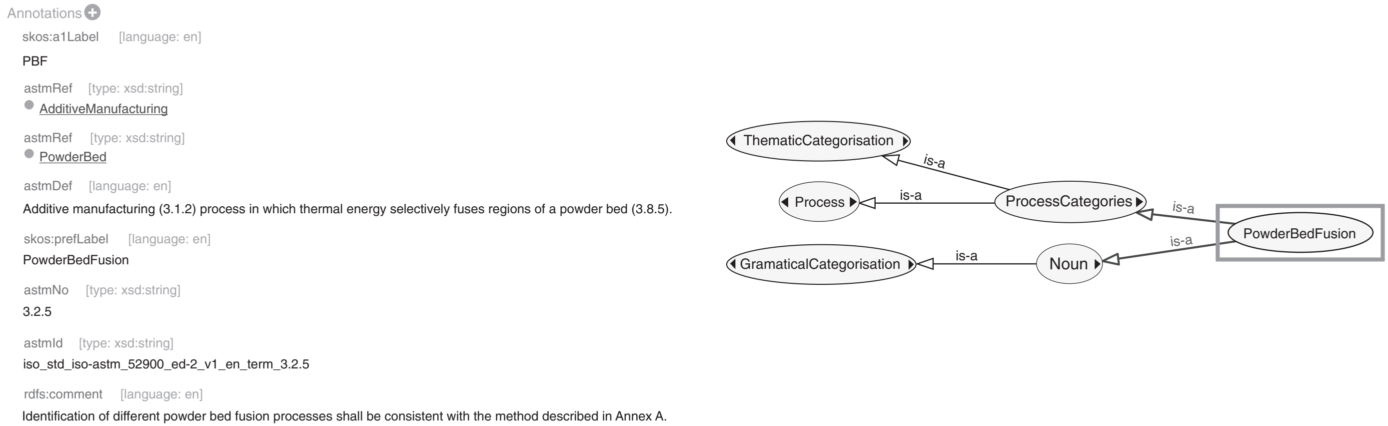

Figure 8.7 Definition and relations for the class PowderBedFusion.

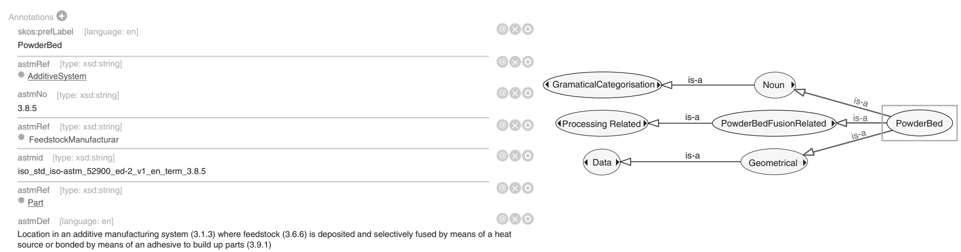

Figure 8.8 Definition and relations for the class PowderBed.

incomplete. It lacks explicit relations between key components of the system, specifically the powder material and the equipment.

The selected papers focus on the effect of anisotropy induced by the manufacturing process itself. From [6], “flat tensile specimens were produced in three sets, each consisting of 11 specimens built at different orientations. The sample orientation with respect to the build plate starts at horizontal (0°), increasing to vertical (90°) with 15° increments”. The concept *BuildPlatform* is defined as an *Equipment,* but it has plural meanings in the previous description as it also refers to the *BuildSurface* (for the first layer) defined as a geometrical object. The definition of the component orientation and position requires a coordinate system: *BuildOrigin* and (*XAxis, YAxis, ZAxis*). Then the *PartPosition* and *PartReorientation* are added and related to the *PositionVector* defined in EMMO.

Important process parameters such as laser power, layer thickness, hatch spacing, and scan velocity are specified in the publication but are not part of this standard. The terms “laser power” or “layer thickness” are considered self-explanatory and something that a qualified user of any AM standard would understand without the need for a definition, and ISO Directives states that they should not be defined in terminology standards. Only the generic concept of *ProcessParameters* is present. The EMMO includes physical quantities that facilitate the alignment. For example, *Power* is defined and associated with *PowerDimension* with the symbolic value “T-3 L+2 M+1 I0 Θ0 N0 J0” for Time – Length – Mass – Electric Intensity – Temperature – Amount – Luminous Intensity. *LayerThickness* would then be defined as a subclass of *Length* and inherit its properties and relations.

In addition, the samples are submitted to different post-process operations. In the standard, only *PostProcessing* is defined as a generic category. In the study, only heat treatment and HIP are used. These processes are generic and not specific to AM and, therefore, would naturally belong in another ontology.

Material and properties

The standard provides a vocabulary to describe the powder material. The primary class, *Feedstock,* encompasses multiple AM processes. In the PBF-LB process, the powder characteristics are crucial. The standard allows users to specify the powder’s source (via *FeedstockManufacturer* and *FeedstockSupplier*) but more importantly, it indicates the possible reuse with *Virgin* and *UsedPowder*. Distinctions in powder preparation are made between *PowderBlend* and *PowderMix* as illustrated in Figure 8.9.

The description of the powder characteristics and part microstructure are not covered by the standard. Therefore, we include an additional existing microstructure ontology[9] based on EMMO. It allows us to define the powder

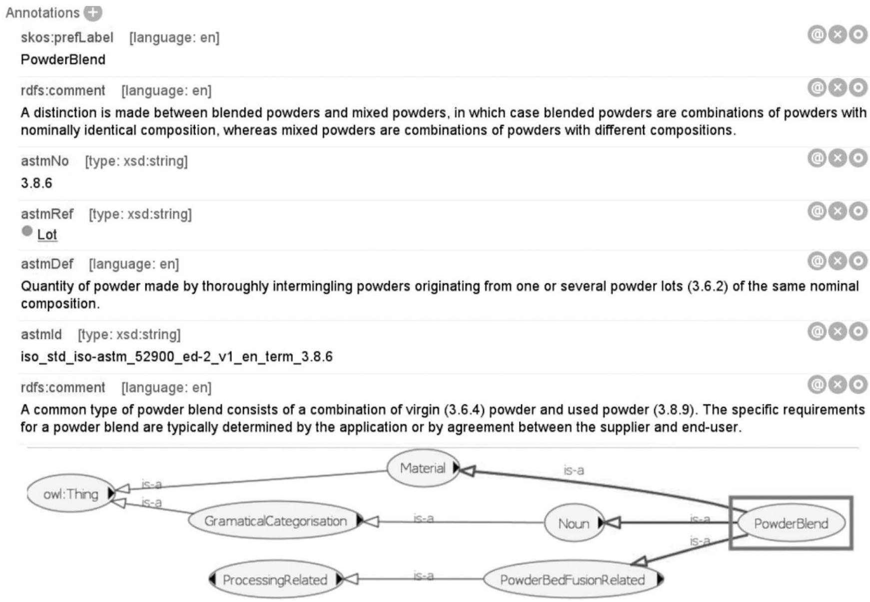

Figure 8.9 Definition and relations for the class PowderBlend.

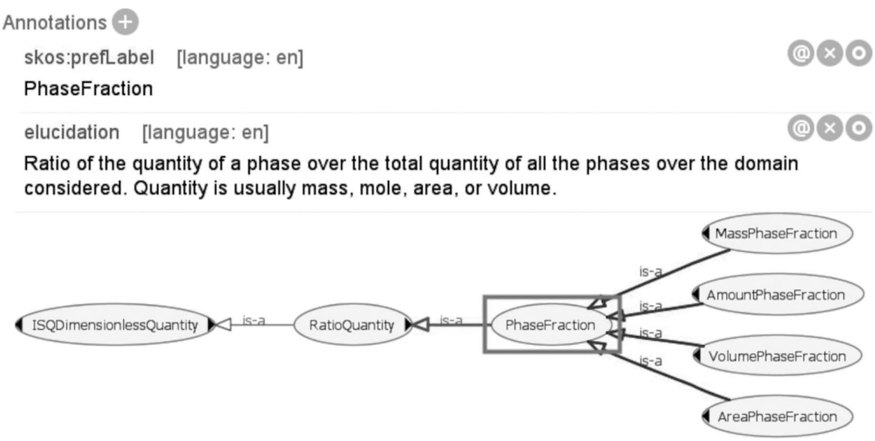

Figure 8.10 Definition and relations for the class PhaseFraction.

composition using the concept *ChemicalComposition*. The anisotropy of the microstructure requires the concepts *MicrostructureMatrix*, *Grain*, *Orientation*, and *EulerAngles* to describe the texture. The microstructure ontology includes *PhasesFraction* (see Figure 8.10), *Dendrite*, *SecondaryArmSpacing*, and *GrainBoundary* to specify the phase distribution and grain structure.

The description of the mechanical properties would require a separate ontology as well, which is not currently available in the framework of EMMO.

Perspective on process and component modelling

In previous sections, the experimental set-up and the process steps have been partly described using the AM ontology rooted in the ASTM standard and additional ontologies. This first step to document semantically an existing process and component enables semantic interoperability. For instance, by defining laser power and path as per the standard, we can automatically generate an input file for process simulation. This is achieved by applying a wrapper layer that links the ontological concept to a model variable and the corresponding input file syntax. Similarly, we can correlate and compare the microstructure measurements with model predictions, such as the average model for grain size or direct simulations using the phase field method. Storing systematic data from measurements, experiments, and simulations within a knowledge graph can greatly aid optimisation studies. The optimisation done by Azar *et al.* [9] requires linking surface characterisation and fatigue modelling by representing the surface roughness effect on crack initiation. Sharing common concepts and representing data in the appropriate format for the different communities is a key to enhance interdisciplinary collaboration.

Reasoning

As previously mentioned, this new ontology only includes information present in the standard and therefore does not pretend to generate a fully consistent ontology. Nevertheless, it allows us to identify the gap between standard documents and functioning ontologies. The semantic storage of all relevant information and measurements for the process, material, and part allows to build a massive knowledge graph. Such a knowledge graph could also include other standards specifying the parameters for efficient production of specific components or structures. The extension with techno-economic data will also unlock production optimisation and decision support (see examples from Nagy *et al.* [10]).

Automated reasoning could be applied when semantic data is based on ontologies. Rules could be extracted to determine the ability to produce a component. For example, a rule might state that if a part is made of aluminium and its minimum wall thickness is greater than or equal to 3 mm, then it can be manufactured additively with constraints on the process parameters and powder composition and sizing. These rules are derived from the data stored in the knowledge graph and can later be applied to assess a design/production proposal automatically. A part satisfying this rule would then be classified as an instance of the *AMfeasible* class.

Concluding remarks

This paper presents the initial effort to partly automate the conversion of the ISO/ASTM AM terminology standard into a functioning ontology connected in a second step to EMMO. The proper formatting of the online document allows us to extract important information and document structure. Nevertheless, the topics and categorisation of terms published in the present edition of this standard are not sufficient to build a complete ontology. Terminology standards and ontologies are developed to serve different purposes, which means that their structures and functionalities don't perfectly match. To build robust ontologies, concepts in the standard must be structured as subclasses of high-level concepts. We have demonstrated that step by relating our concepts to the top-level ontology of EMMO. The resulting ontology could be evaluated with online tools (like OOPS[10] and FOOPS[11]). As expected for this preliminary work, the score is mitigated. OOPS returns minor pitfalls due to the incompleteness of the class (lacking, for example, standard annotation) and an important one with respect to the lack of disjoint axioms. Similar remarks are provided with FOOPS and additional ones related to availability. These results reflect the immature level of this ontology and the limitations of automatisation. Future work will need to address these shortcomings to provide a robust ontology.

The AM ontology was then applied to describe existing research work. As the selected standard focuses on production, the AM ontology does not encompass all concepts mentioned in the referenced paper. This highlights the need for more comprehensive ontology development in both AM and materials science. By incorporating the microstructure ontology developed under the EMMC framework, we were able to address most microstructure concepts.

The growing integration of material and process modelling in component design and manufacturing will require the coupling of multiple models. The present work showed partly how the development of domain-specific ontologies will enable semantic interoperability, thus greatly accelerating the integration of new models in simulation workflows. In the future, it is anticipated that all numerical models will need to semantically describe their inputs and outputs for widespread use and integration in modelling software marketplaces.

The terms and definitions of ISO/ASTM 52900 are freely available through the ISO Online Browsing Platform; similarly, the AM domain ontology is released on a public repository under the Creative Commons Attribution 4.0 International license (CC BY 4.0). It allows any manufacturer, designer, or modeller to rely on the common vocabulary and integrates semantics at no cost. Standards are more than just term definitions. The fundamental need for clarity, consistency, and coherency, as well as ensuring the openness and transparency of the process and a clear procedure for establishing consensus agreement and the publication of the standard, requires significant administration and clear directives, and this costs money. Currently, the users pay for accessing the standards documents, so the costs are covered by those who need, use, and benefit from them. In the future, standards will need to be integrated into the digital world within knowledge graphs to enable smart manufacturing. This work can be seen as a small step in that direction, where research work begins to be documented semantically based on ontologies covering production, materials, and processes. Later, the user could buy fully ontologised standards and ensure their application by computer reasoning on the stored data.

In the short term, we will aim at expanding the existing ontologies to cover the necessary measurements, simulations, and experimental set-up to completely describe our work. The objective is also to strengthen the connection to EMMO by exploiting the symbolic description of models and enhance interoperability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article. While Jesper Friis is a major contributor to EMMO and SINTEF was a beneficiary of the EMMC-CSA project (2016–2019) leading to EMMO publication, these roles are not considered as inducing bias in the presented work or as competing interests.

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Notes

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Chapter 9

Digital farming in Kenya under COVID-19

How digitalisation enables market expansion strategies and asymmetric power relations in the global production network of fertiliser

Amalie Østhassel

Introduction

In light of recent pressures on our global food system, East-Africa has been brought forward as the potential "breadbasket" of the world and is calling for increased investments whereby "digital farming" is used as a carrot to attract youth and capital. Hence digitalisation as a tool to upgrade agricultural activities is at the forefront of the agro-industrial research agenda. Fielke and colleagues [1] emphasises how agricultural digital trends influence the transition pathway of agricultural activities towards more or less desirable outcomes. As such, this study builds on the work of the downstream end of the global value chain of chemical fertiliser by Tups and Dannenberg [2] and how digital tools enable governance in value chains by Butollo and colleagues [3]. This chapter will focus on how the distribution of chemical fertiliser in Kenya by Yara International is augmented through digitalisation and strategic partnerships that capitalise on narratives presented by dominant leaders in the development space. It argues that the strategic deployment of digitalisation in a conditioned institutional space enables access to favourable conditions for market development among agro industrial businesses. Ultimately, this paper adds to our understanding of how lead firms within GPNs continue to control farmers and indirectly our global food production.

Literature review

Role of digitalisation as part of the market expansion imperative in global production networks

In the neo-Schumpeterian era of global development, where innovation is understood as a core driver for economic growth, the fact that the analysis of technical developments and institutional change helps us understand economic

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relationships is undisputable. Nonetheless, a core objective of studies of the global economy is to understand the shifting patterns of uneven development and how the "global shift" of economic globalisation is being driven by the convergence of information technologies [4]. As such, the emerging literature on digital value networks [5,6] seen through the lens of the seminal work on digital capitalism by Schiller [7] is relevant in the study of how digitalisation affects governance and power dynamics in global production networks (GPNs). Especially with the rise of emerging economies in the Global South and the capitalist imperatives by multinationals to develop new markets through the capitalisation on digital revolutions in countries with vast potential [8]. Moreover, GPNs have the potential to act as channels for the transfer of global knowledge and technical know-how and therefore play a crucial role in the innovative transformation and economic development of countries and regions. As such, Yeung and Coe [8] call for more research on market developments in GPN literature and highlight the need to understand the dynamics of the market creation process by fully acknowledging the role of both customers and producers in the shaping of new demands and capabilities. Hence, there is a limited pool of literature delving into the downstream end of global value chains as an extension of the market development imperative.

However, Dodge [9] adds new insights into the value-added component of market development in resource peripheries and emphasises how the literature tends to concentrate on the economic dilemmas surrounding resource extraction rather than exploring the downstream aspects of market development in such regions. Focusing on the production of natural gas in Indonesia and Myanmar, Dodge finds that authorities play a crucial role in reconfiguring the positionalities of resource peripheries in nation states; hence, market development is not a static concept but rather relationally conditioned and changes over time. Also focusing on the downstream end of the global fertiliser industry, Tups and Dannenberg [2] find that strategic couplings between GPNs and regional assets play a significant role in shaping market developments in agricultural markets. They investigate the mobilisation of the Southern Agricultural Growth Corridor of Tanzania (SAGCOT), a development corridor initiated by the Tanzanian Government to attract agricultural investments with the aim to transform agricultural value chains and ensure the commercialisation of smallholders' production. A highly complex process, the authors argue that spatial imaginaries, such as SAGCOT, serve as sources of power in coupling processes between corridor regions and GPNs. They distinguish between "emptying the future" and "claiming space" as two fundamental mechanisms of spatial imaginaries and argue that the power of spatial imaginaries in coupling processes relies on maintaining persuasive arguments about the future. Only when spatial imaginaries succeed in maintaining such arguments can they initiate and stabilise otherwise unfavourable coupling processes. In addition, the work by Li et al. [10] on industrial upgrading in the Chinese apparel industry investigates the role of e-commerce companies and finds that the emergence of internet-based platform companies has led to the formation of "two-sided markets". They argue that traditional linear value chains have been disrupted by the displacement of traditional retailers by online sales and that consumers and platforms are more directly involved in value creation, thus shifting the power from retailers to individual consumers. Finally, Howson [6] argues that both producers and consumers are involved in developing new demand conditions and supplier capabilities in the digital platform economies.

Digital power and big data to inform new directions of global production network research

Moving forward, Foster and Graham [5] adapt the GPN framework to understand the influences of digital information systems in economic production processes using illustrations from the East African tea sector. They argue that globalised production networks are increasingly relying on institutional information communication technologies (ICT) and digital configurations to enable more efficient flows of monitoring and evaluation. Expanding our understanding of embeddedness within the GPN framework, they argue that the socio-technical bundle of ICT activities includes digital information flows, digital technologies as tools of production, and digital data derived from these activities. They refer to this as "the digital" and highlight how its role within the GPN framework has been limited to that of an infrastructural component within production networks. Consequently, an emerging body of literature focuses on the digital transformation of value chains and how digital platforms are part of a larger concept called the "digital value network" (DNV) [6]. This direction of research has mainly been centred around the role of digitalisation on unpaid labour transactions favouring global North actors [11] and how digital platforms are emerging as new types of lead firms in cross-border networks [12]. Others are calling for more research on the recentring of value in the digital transformation in GPN literature [13] and the role of data as a specific form of intangible resource in the governance structures of value chains [3].

Moreover, Lang et al. [14] claim that power asymmetries play a crucial role in shaping global value chain (GVC) participation and can exacerbate inequalities within and across nations. They argue that the concept of power in GVCs is not limited to direct market power but also includes diffuse conceptualisations that focus on social construction and legitimacy, which can influence power dynamics and value capture in a telecommunication standard setting. In a similar account, Oliveira and colleagues [15] suggest that digitalisation can shift power relationships within GVCs, leading to a concept called "digital power" that captures the power imbalance experienced by suppliers in relation to lead firms in value chains with different degrees of digitalisation. Additionally, Gallemore and colleagues [16] found that proprietary technologies favour established lead firms and emphasise that accessibility through open monitoring technologies in the GVC will enable more inclusivity and access to greater exchanges of knowledge. Subsequently, Rivera [17] views digitalisation as a new stage of capitalism and argues that increased digital power through technological ownership enables companies to create new regimes of accumulation and social control beyond their products and market share. In summary, there is a limited pool of research that adds to our understanding of how the strategic deployment of digitalisation enables digital platforms to emerge alongside "traditional developments" in new markets. Hence, the role of big data as captured through the mobilisation of digital technologies by lead firms as a strategic fabric that aims to configurate networks, retrieve consumer needs and "claim space" in the creation of new markets has so far not been explored in the GPN literature.

Methods and data

This research uses the case study of the COVID-19 initiative *Action Africa* to understand Yara International's strategic positioning and mobilisation of digitalisation to sustain and expand their market share as a supplier of chemical fertiliser to Kenya. The case study was identified using snowballing methods whilst building on an inductive and bottom-up approach to qualitative data analysis of Yara's digital farming strategy. As the study transgressed, the importance of the initiative as a catalyst for Yara's digital farming strategies on the continent became clear. From early 2022 to October 2023, the researcher conducted 33 semi-structured stakeholder interviews with relevant stakeholders (Table 9.1). Additional supportive material comes from observations of the helpdesk for digital farming services in the Yara Nairobi office, field visits to Yara customers and retailers around the North Rift Valley in Kenya (including a centre of excellence/Yara outlet), in addition to participation in industry conferences and panel debates.

The main purpose of the field visits to farms and retailers was to understand how the digital farming platforms operated and the motivation for why they were being used. In addition, a document analysis was conducted to validate interviews and understand relevant timelines during the COVID-19 response and launches of the various digital platforms. This consisted of a combination of annual reports, news articles, press briefings and social media. Specific numbers of downloads, registrations and impacts have been collected and triangulated from a combination of interviews, annual reports and online publications. All analysis of transcriptions, documents and fieldnotes was carried out with the use of NVivo software.

Table 9.1 Overview of data

Type of data	*Amount*	*What*	*Location*
Interviews	33	Yara Representatives from Yara's country team in Kenya (both managerial and operational, specifically working with digital) Action Africa associations Norwegian Ministry of Foreign Affairs (NMFA), African Fertilizer and Agribusiness Partnership (AFAP), Alliance for a Green Revolution in Africa (AGRA) Consultants & Policy (Norad, One Acre Fund, Innovation Norway, Cereal Growers Association) Civil society Anonymous stakeholders	Nairobi Online
Retailers/ Agrovets	6	Agrovets selling farming inputs, incl. Yara products. 3 retailers registered on the Bodega platform	Eldoret, Kenya
Yara customers	7	Medium- and large-scale farms	North Rift Valley Meru Nairobi
Yara Centre of Excellence	1	Large-scale farm	Eldoret, Kenya
Events	11	Seminars, conferences, workshops, webinars and panel debates	Nairobi/ Oslo/ Online

Findings and discussion

Norwegian manufacturing giant in Kenya: Yara International

Yara International demerged from Norwegian Hydro in 2004, leaving the oil and gas industry to become a global leader in the production and distribution of chemical fertilisers. It produces all upgrade steps of ammonia-based fertilisers, including urea, nitric acid, nitrates, and nitrogen-based compound fertilisers (NPK). With main production sites in Norway and Europe, Yara is the second-largest producer of ammonia globally and the world largest producer of NPK. In 2021, Yara established a clean ammonia unit and a joint venture to develop Europe's first full-scale green ammonia project in Porsgrunn, Norway. In 2022, Yara's sustainable governance procedures were

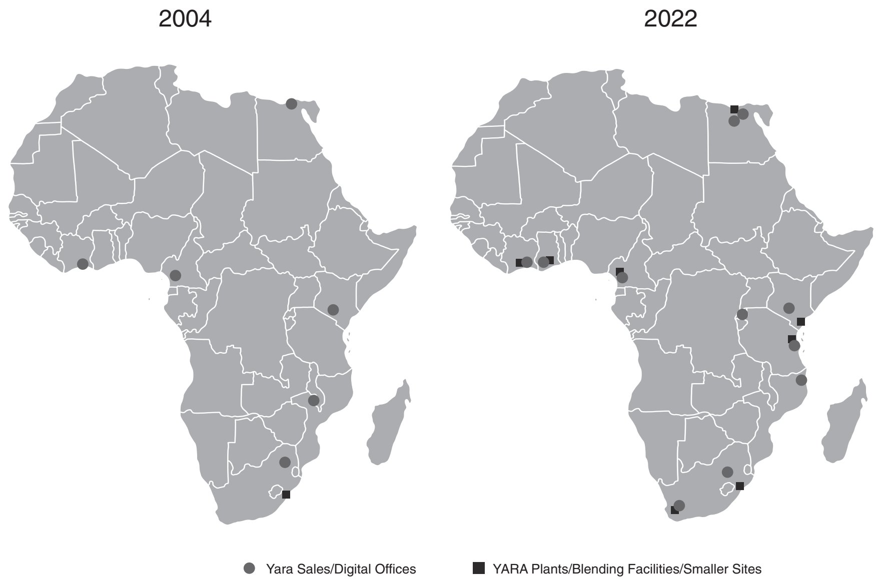

Figure 9.1 A map of Yara's market expansion in Africa in 2004 versus 2022.
Source: Authors own illustration based on Yara Integrated Reports 2004–2022.

given the highest score by Cicero, a leading Norwegian climate research institute. Yara specifically received attention for their investments in carbon storage, the production of green ammonia, and the agronomic efficiency of their premium fertiliser products [18]. Yara's Digital Farming Unit was established in 2018 and states that they aim to become the global leader in digital crop nutrition. They refer to this as digital value creation, which is part of a future business model that is based on a digital services business that commercialises their farming knowledge. By 2023, Yara had around 17,800 employees and 28 production sites across six continents, with 40% of its markets in Europe.

Dating back to the 1970s and financed by development aid, Yara was granted market access in East Africa through small sales in Kenya, Tanzania, Zambia and Uganda. Their first office on the continent opened in 1985 in Zimbabwe, and by 2022, the company had ten sales offices, eight plants and distribution sites, and one digital hub across the continent (Figure 9.1). Yara is one of the fifth-largest players on the African fertiliser market, with Yara MiCROP, their most affordable fertiliser for maize production, being the most popular product. In Kenya, both affordable MiCROP (NPK) and premium products such as YaraVita are known among Kenyan farmers as the more expensive yet better quality products in terms of both yield optimisation and soil conservation compared to other alternatives on the market. In 2023, the African continent was Yara's least profitable market yet the fastest-growing one, with a 36% increase in sales and market deliveries from 2018 to 2019,[1] making it a key market for future long-term investments.

Precision farming and the Kenyan digital revolution

East Africa has the potential to be the food basket of the world, considering the favourable climatic conditions for agriculture. Global food demand is expected to grow by 63% by 2050 [19], which makes access to fertiliser for African nations vital for improving food production. Following the Africa Fertiliser Summit in 2006, members of the African Union came together and declared fertiliser a strategic commodity without borders under the Abuja Declaration. They agreed to increase fertiliser use from 8 kg per hectare to at least 50 kg by 2015. However, by 2021, the average rate of fertiliser application in SSA is 22 kg per hectare, compared to the EU average of 150 kg. Norwegian farmers use more than 200 kg for the same (Figure 9.2). For African smallholder farmers, this lack of access to fertiliser combined with the huge knowledge gap for its application is a key constraint for increasing food production [20].

According to the EU, feeding the world responsibly means to increase food production whilst maintaining soil health, conserving biodiversity, preserving cultural heritages and being commercially viable on a long-term basis [21].

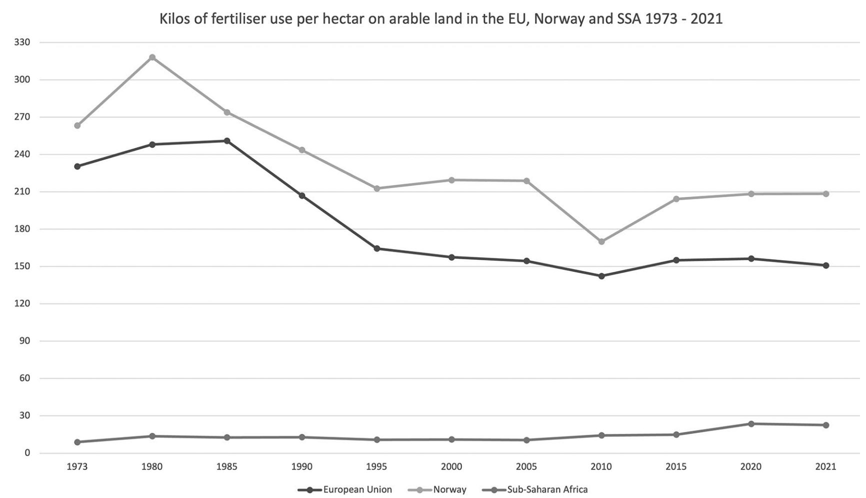

Figure 9.2 Kilos of fertiliser use per hectare on arable land in the EU, Norway and SSA 1973–2021.

Source: Authors own illustration based on calculations using World Bank Data (2022).

Hence, precision farming has been brought forward as a method for the sustainable intensification of agriculture [22]. Precision farming is the utilisation of georeferencing data and farmer-centred technologies such as soil testing kits to inform better on-farm management in terms of fertiliser and pesticide application to optimise production and commerciality. Although there is not an agreed-upon scientific definition of precision farming, Gebbers and Adamchuk simply put it "as a way to apply the right treatment in the right place at the right time" [23]. It is a knowledge-intensive method, and Yara believes that the use of digital tools can help close this knowledge gap for African farmers. To underscore the importance of closing the knowledge gap for the use of fertiliser in precision farming, a senior manager at Yara emphasised that; *"People don't understand that we walk in with a bag of the Yara Mila which is 10 times the price of a bag of urea, they don't know the balance nutrition and how much more you will get from our products"*.[2] Hence, at the core of Yara's digital farming strategy is the knowledge gap for the correct uptake of multi nutrient fertiliser blends, which has been brought forward as a key challenge for enhancing sustainable food systems in Kenya [24]. Studies find that precision farming as a sustainable farming practice is an evolving concept that is largely informed by the agri-business sector [25], and Yara promotes itself as "taking the lead in developing digital farming tools for the precision farming".[3]

Moreover, digitalisation has been emphasised as a key factor in an alternative industrialisation strategy for Africa, and there is an emerging pool of literature focusing on "industries without smokestacks" or the so-called "servicification of manufacturing" pathway [26]. The Kenyan government have invested heavily in ICT infrastructure since the first sea cable link came in 2009, connecting the East African country to cheaper and faster internet access than the previously used satellite connection. At the same time, the world's first mobile banking solution was developed in Kenya and was considered "the most influential and inclusive fintech innovation in the world" by Forbes Magazine in 2022. Evidently, since its launch in 2007, M-Pesa has become the main digital banking tool for its 30 million Kenyan users, connecting rural and urban areas and allowing cash free transactions across communities. By 2022, 95% of the Kenyan population was covered by at least 3G mobile networks, and almost a quarter of these have a smartphone with access to apps [27]. This digital revolution has led to a spike in interest in research that explores the impact of digital connectivity on increased livelihoods among smallholder farmers in Kenya. One study finds that the adoption of smartphones has had a positive impact on the upstream end of the horticulture value chain, with smallholders reporting improved access to market information, increased bargaining power with intermediaries, improved access to financial services and the ability to participate more effectively in value chains and generate higher incomes [28]. However, the study also highlights some of the challenges associated with smartphone adoption, such as the cost of devices and data and the limited availability of relevant digital services and knowledge. Nonetheless, trust in digital tools is high among the Kenyan population, and farmers easily adopt new digital agricultural technologies.

COVID-19 humanitarian response as a source for Kenyan farmers personal data

As the COVID-19 pandemic spread rapidly across the globe in early 2020, concerns of food security and increased hunger across African nations became a key priority for the Norwegian development agenda. The World Food Programme warned of "famines of biblical proportions", with up to 300.000 people dying of starvation every day,[4] whilst then Norwegian Development Minister Dag-Inge Ulstein called for public-private initiatives to protect the most vulnerable,[5] especially in Africa. This window of opportunity was emphasised by Yara's CEO in the annual report from 2020 where Yara's role in the pandemic was framed as being called upon by WFP Executive Director David Beasley, who had told Yara to "make sure you get your product out to the farmer"[6] warning of a global hunger catastrophe if they failed to do so. Arguably, such narratives of scarcity and the anticipation of hunger crises enabled agri-business players the opportunity space to leverage "silver linings" [29] to claim space and seize opportunities to expand their market presence. In the case of Yara, this was done by capitalising on farmers personal data to expand their ambitions and develop their value proposition on African markets.

In June 2020, Yara launched the "Action Africa: Thriving Farms, Thriving Futures" initiative as a humanitarian response to the global pandemic. Action Africa aimed to donate 40,000 metric tonnes of fertiliser (valued at $25 million) to support 250,000 smallholder farmers in seven countries in East Africa, where Kenya was included. Financially, this was a minor contribution for Yara, as the total delivery of crop nutrition products from Yara to African markets was 1,182,000 metric tonnes in 2021.[7] According to Yara, Action Africa was a partnership between the Norwegian Ministry of Foreign Affairs, the World Food Programme, the AGRA, and the AFAP. Even though no formal agreements have taken place, they have all publicly supported the initiative as part of Yara's marketing strategy. By July 2020, two vessels shipped Action Africa-branded Yara Mila Cereal (a premium product) fertiliser from Porsgrunn in Norway to the ports in Mombasa and Dar es Salaam, where it was received by government officials and Yara staff alongside promotional Facebook campaigns under the hashtag #FoodChainHeroes and reported on among several national news outlets in Norway, Kenya and Tanzania.

Building a digital distribution chain in times of crisis

To deliver the donation of fertiliser efficiently and at scale, Yara developed a registration platform that collected contact information, farm size, crop type and location of farmers in less than 45 days with their partner Thoughtworks. Farmers registered through a mobile solution and would receive an OTP code to redeem their free Action Africa-branded 50 kg of Yara Mila Cereal fertiliser at the nearest Yara retailer. Yara retailers in Kenya were already using the Yara Connect platform, a reward-based loyalty programme where retailers could redeem points for selling Yara products. The retailers were encouraged to help farmers apply for the COVID-19 initiative and would use QR codes to register the Action Africa fertiliser and thus be eligible to redeem points for the donated fertiliser (Figure 9.3). This was unique for the case of Kenya, as the digital distribution system through Yara Connect and traceability through QR codes were already established tools in the value chain due to the deep technology penetration and high digital trust in the Kenyan

Figure 9.3 QR codes to redeem points and enable traceability by a Yara Retailer in Eldoret, Kenya, in 2023. Photograph by the author.

market. Additionally, traceability was a key concern for the credibility of the project as a development initiative, and one Yara representative said, *"There's a lot of corruption, right? Many people have tried to do this before. And it's sad but true. So this was a fool proof system with us using our Yara Connect system for scanning QR codes. We could literally track and tell you this batch code of fertiliser went to Farmer X, Y Z"*.[8] By January 2021, Yara reported that the overall Action Africa initiative had delivered 140,000 bags of fertiliser (equivalent to 7,000 metric tonnes), registered almost 2 million new farmers in their system and connected more than 450 retailers in a new supply chain.[9]

Action Africa data to inform a new direction of service delivery for Yara International

The agricultural transformation debate in Kenya is continuously trying to balance the economics of farmer livelihoods on a micro level with the conservation of the ecosystem on a macro level: *"Increasing production for production sake is not the solution. It also increases food loss and food waste and contributes more to emissions and climate change"*.[10] Aligning with this statement from AGRA, Yara's vision of becoming a knowledge hub for farming services in Kenya was emphasised when a representative from the digital team said, *"We want to create a closed looped system for all farmer needs and empower the farmer through digitalisation"*.[11] Yara argues that with their role in the downstream value chain and supply of fertilizer, they have a responsibility in terms of advisory in the rural economy; *"knowledge and advisory will lead into building up and preparing the rural economies into tapping into capital, which will then also lead to affordability of farming inputs"*.[12] These statements confirm the overall vision of Yara to become the key service provider for farming inputs in Kenya. Hence, the ownership of data on soil health, digitally stored data on farmer's needs, and geo-locations of customers (both farmers and retailers) are part of the big data pool, which has become central to the value proposition and service delivery of multinational agri-business on the African continent.

Yara gained access to such a pool of big data under the Action Africa initiative, where farmers had to consent to Yara owning and storing their acquired data in order to receive free fertiliser under the terms and conditions on the online registration form. However, it is unknown to what extent farmers were aware that their data would be used for future business development purposes. According to Yara, all farmers privacy rights and digital agency were considered by their marketing team, which ran educational campaigns: *"We have educational campaigns, educating the farmer exactly how the probate process works. That means with registration, what would be done with your data, permissions with your personal data"*.[13] However, several retailers mentioned how they often "helped" farmers fill out the application form to

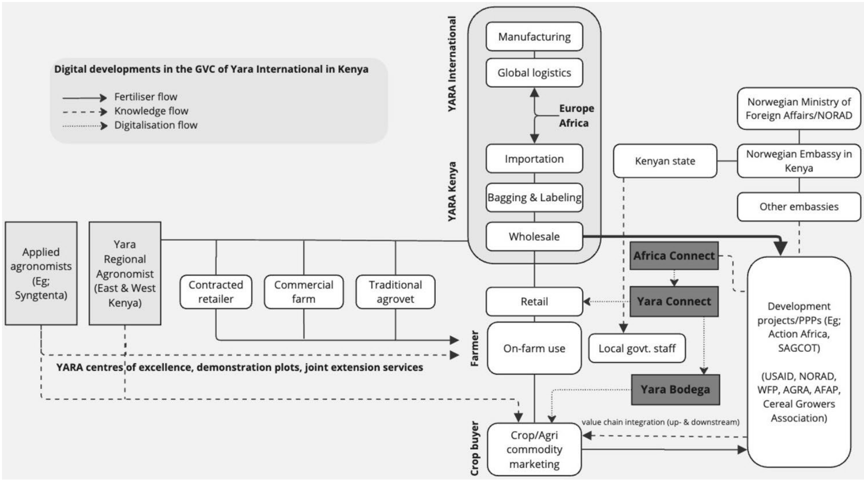

Figure 9.4 Digital developments in the GVC of Yara International in Kenya.

Source: Authors own illustration adapted from Tups and Danneberg (2023).

be eligible for the Action Africa fertiliser. This would allow them to redeem points under the reward scheme using the QR codes. Partners of the initiative emphasised that many processes during the pandemic "felt a bit rushed" due to the unknowns around the pandemic and the necessity of getting "fertiliser out there".[14] At the same time, when registering for the free fertiliser, farmers would not be eligible if they did not accept the terms and conditions of giving Yara ownership of their data. When asked about this, Yara said that nobody said no to their terms and conditions. If that had been the case, Yara confirmed they would not have received any free fertiliser as Yara would be unable to contact them. Later, Yara integrated the collected data from Action Africa with the marketing platform Africa Connect, a digital platform where users receive offers of fertiliser and seeds and where to purchase them by SMS. Africa Connect had up to 1 million registered farmers in Kenya from the Action Africa initiative.[15] Following feedback from farmers that the marketing push through Africa Connect was "too aggressive",[16] the users were migrated into Yara Bodega, an online marketplace platform that has been merged with the retailers reward platform Yara Connect (Figure 9.4).

Yara Bodega as a key digital tool in Yara's market expansion strategy in Africa

Historically, private-public partnerships (PPPs) have been an integral part of Yara's Africa strategy for decades, and the fertiliser giant is known for its aggressive downstream market expansion on the continent [2,30]. Through the capitalisation on the crisis narrative of global hunger by leveraging PPPs with institutions like the NMFA, AGRA and AFAP that enabled the Action Africa initiative and gave Yara data insights of up to 2 million farmers, Yara extended their digital farming strategy in Kenya and launched the Bodega platform in April 2023. The Bodega platform is an online marketplace of farming inputs and, at launch, offered a wide range of products and services, from fertiliser and seeds to tractor rental schemes and irrigation systems.[17] According to Yara, the farmers who are registered on the Bodega platform were given the opportunity to receive offers from third party actors in addition to Yara, for example, crop insurance or credit schemes from banking providers. Consequently, Yara's service delivery consists of bundles of programmes with products from a variety of strategic partnerships that align with Yara's precision farming methods and are being offered at scale through their digital farming strategy.

The Bodega platform is a tool in the wider digital farming strategy of Yara and also aims to offer services using advanced technologies such as drones to apply very small amounts of pesticides or fertilisers in certain locations, thus leveraging basic economies of scale. Highlighting the future vision of Yara's distribution network, a representative from the Yara digital team said: *"(Drones) will help in almost creating clusters (of farmers) that are more centred than the current retail network of many service providers (retailers) which is based on the road network, marketplaces and not on where is the cultural land…". In future, you could find that an online retailer like Bodega may not need to have a physical shop anywhere"*.[18] Consequently, the development of the Yara Bodega platform enables Yara to develop a business model that not only goes in parallel with their traditional market and physical distribution infrastructure but also builds digital value chains using advanced drone technology for service and product delivery. As such, Yara creates a "two-sided market" as they enter a new mode of service delivery using internet-based platforms as a strategic enabler of their manufacturing core business, allowing them to scale their business through a digital strategy at an increasingly efficient pace based on and with full ownership of the accumulated big data from initiatives like Action Africa.

Conclusion

In summary and adding to the work of Tups and Dannenberg [2, 31] on the global fertiliser trade in East Africa, this article places digitalisation as a core component within GPNs and value chains, not only as a strategy to develop new markets through data insights but also as a governing tool to direct the future of agricultural development on the African continent. As exemplified by the Action Africa initiative by Yara, the capitalisation on the crisis narrative of "global hunger" during the COVID-19 pandemic created a window of opportunity for large agri-business players such as Yara to claim space and secure data insights through strategic partnerships. The digital power aided by the Action Africa initiative enabled the ownership of data and digital platforms, which is vital for the development of new service delivery and Yara's "two-sided market" expansion in Kenya. The process in which such data insights from farmers were secured is uncertain, exposing the uneven power balance that exists in agricultural GPNs between firms and consumers, which are augmented through digitalisation. Arguably, the (mis)use of such digital power has the potential to not only secure future markets for large multinationals but also maintain the direction of knowledge economies in the definition of and access to sustainable agriculture, thus controlling farmers and indirectly our global food production.

Notes

1 Yara International ASA 2019 third quarter results, p 17.
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Novel manufacturing processes and materials

Chapter 10

Possibilities and challenges of using robot manipulators in additive manufacturing (AM)

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Robotisation of AM processes

In this section, we present a discussion on the advantages and shortcomings of using articulated robotic manipulators (i.e., robotic manipulator arms) for two additive manufacturing (AM) processes, which are directed energy deposition (DED) and material extrusion (MEX). Two different DED processes with metal and polymer feedstocks are considered, Wire-arc and laser DED for metallic materials, while for polymers, we look at the most applied AM process, namely the MEX process.

Introduction to AM processes

DED are AM processes in which focused thermal energy is used to fuse materials by melting as they are being deposited [1] (Figure 10.1). These production technologies consist of a feedstock material in the form of metal wire or powder. The heat source can be one or more lasers, electric wire arcs, an electron beam, or plasma. The first two are the most common ones, and there are also variants that combine different heat sources or different feedstocks.

Laser melting is quite versatile and depends on many parameters. The wavelength, power, pulsing, focus, and beam shaping are part of the picture. Combining this with the use of several lasers, feed of material, heating of substrate and material, robot movements, etc., the parameter window becomes enormous. However, most available systems come with one material form and one laser. Often, this is a powder-fed system with a powerful fibre laser with just over 1,000 nm wavelength. These systems offer speed, size, and flexibility. It has the possibility to produce fine details and has a relatively low impact on the substrate, but it is in no way as fast as wire arc or electron beam methods. DED systems with laser melting are possible to automate by attaching a building head to a robot flange; however, special safety considerations should be accounted for.

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The manufacturing method Wire-Arc Additive Manufacturing (WAAM) uses a wire-arc welding process as its thermal energy source (Figure 10.1). A welding gun and the heat input from an electric arc are used to weld metals together. The most used arc-welding method in WAAM is gas metal arc welding (GMAW), also known as MIG/MAG (metal inert/active gas) welding [2]. When using GMAW, the welding wire deposited by the welding gun works both as a filler wire for the building process and as an electrode. The welding gun can be attached to a robot manipulator, and material can be deposited along a pre-programmed path, making the method possible to automate. Gas tungsten arc welding (GTAW) is another method that can be used for WAAM, but GTAW uses a non-consumable tungsten-alloy electrode inside the weld gun. The filler material is added to the welding process separately from and in front of the welding gun along the motion path. This means that a rotational degree of freedom (DOF) around the welding gun axis becomes an important process control parameter when automating the process, which is an additional complication compared to GMAW. The wire feeder is also an additional physical obstacle, which should be considered when doing path planning for a robotised and autonomous system. Plasma arc welding (PAW) is another type of arc welding that also uses a non-consumable electrode and a separate filler wire, which leads to the same complications as the GTAW process. This is the main reason why GMAW is more commonly used for WAAM than the two other arc welding methods.

Several of the advantages of using WAAM compared to other manufacturing methods for metal structures are listed by Williams et al. [3]: Investing in the equipment is both relatively low-cost and low-risk, as both welding equipment and industrial robot manipulators are available in a lower price range compared to more specialised equipment and can be re-sold or used in other parts of production if necessary. Depending on the demands on the material quality of the product, the building method is not restricted by the size of a building chamber, as building materials such as aluminium or steel do not require an inert atmosphere for the building. Then the size of the structure is only limited by the collision-free workspace of the robot manipulator, which can be further expanded using rails or a gantry system. An enclosed chamber is necessary when using, for example, titanium to create an inert atmosphere for gas shielding. WAAM has gained much interest in the industrial manufacturing sector because of the possibility of a high deposition rate. Deposition rates for WAAM typically vary between 1 kg/h and 4 kg/h, meaning that it is possible to produce larger parts at a reasonable rate, though this depends on the material and process parameters [4, 5].

MEX is a well-known AM process for polymer products that can both be used for production and rapid prototyping (Figure 10.1). The general steps of a polymer MEX process are as follows: the material is fed at a constant rate through a building head, where it is softened by a heating element and pushed through the nozzle. The nozzle is normally positioned over and in close vicinity of the underlying layer, such that the softened material is pushed towards

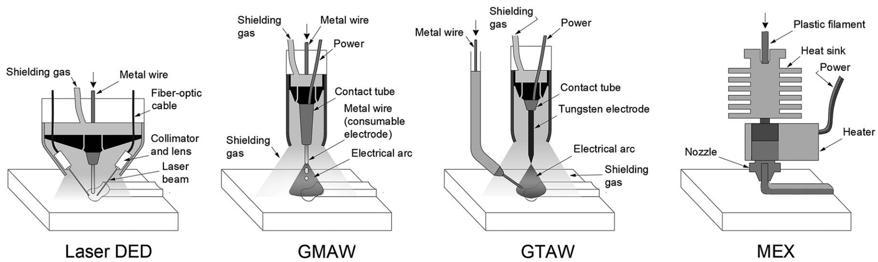


Figure 10.1 Schematic drawings for several AM processes.

and bonds with the previous layer. For many materials, it is beneficial to preheat the building plate to facilitate the bonding of the first layer.

The commercial product range is large, starting with small and relatively inexpensive extruders such as Prusa i3 MK3S and up to large robot-mounted extruders such as Massive Dimension MDPE10, which has a deposition rate of up to 4.5 kg/h. The two above-mentioned products represent two different types of polymer MEX in terms of the material feed system. Prusa i3 utilises a polymer filament feeding system, while MDPE10 has a polymer pellet feeder.

Cartesian manipulators are the dominating robotic platform for industrial implementations of DED with laser melting and polymer MEX processes. Such manipulators have only three translational DOFs and cannot change the tool orientation. This means that deposition is done layer by layer along one axis, with a limited possibility of non-planar layers and reorientation of the build axis [6]. As layer orientation and layer curvature affect the mechanical properties of the part [7, 8], the choice of the kinematics of the manipulator may be important for the mechanical properties of the resulting part. Utilisation of 6-DOF robotic manipulator arms for AM processes has largely been done by the research community. MEX using a 6-DOF robot manipulator was also performed in work within SFI manufacturing: in 2017, a cup structure was built in viscous glue deposited by a caulking gun attached to a robot manipulator in order to demonstrate a building process that was not based on layers but rather a path with a continuous increase in the vertical position of the tool [9]. Several new commercial AM systems have, however, been made available on the market, such as the Meltio Engine DED system with laser melting or the Massive Dimension MDPE10 polymer MEX system. Both can be installed on 6-DOF robot manipulator arms. It is worth noting that WAAM processes normally utilise general-purpose robotic welding equipment installed on a 6-DOF robot manipulator arm.

Process time and cost

Generally, wire-based DED processes using wire have a low cost of usage. For higher-range metal production equipment, the cost may be between 200,000 and 450,000 Euros. This kind of single-wire equipment can generally add

0.5–5 kg/h. The material cost is the same as for welding and varies a lot according to the material. Carbon steel can be bought under 1 Euro/kg, while some nickel alloys may have a kilogram price above 300 Euro. The main costs are the equipment, operator, and post-processing of parts, while the costs for maintenance, software, and gas are negligible. A 450,000-Euro system applied for 1,500 hours per year, with a down payment over five years, will cost 60 Euro/h. A 316 L stainless steel 1 mm wire costs 3.5 Euro/kg, and an operator costs around 50 Euro/h. Given that, even at the 5 kg/h processes, equipment and operator costs are the main expenses.

Advantages and shortcomings of using robotic manipulator arms

Industrial robot arms are an integral part of modern manufacturing environments and have been since the introduction of the Unimate in 1961 [10]. The general advantages of industrial robot arms over special-purpose machinery were outlined by the creator of Unimate, Joseph F. Engelberger, in his book "Robotics in Practice" from 1983 [11] and still hold true today: industrial robot arms are off-the-shelf products, meaning that they are readily available in various sizes and cost ranges, they can be used for many different tasks, and their broad userbase results in more information available for debugging, more funding available for development, and more skilled operators available for hire.

Most industrial robot arms are composed of six serially linked revolute joints, generally partitioned into three joints to position the wrist centre and three joints to orient the end-effector around the wrist centre [12]. These are sometimes referred to as articulated robots and have a large reachable workspace with respect to their footprint when compared to other kinematic structures such as generalised Stewart platforms and Cartesian manipulators. A subset of the workspace is also reachable with any arbitrary orientation of the end-effector. This means that the robot arms can deposit material in non-planar layers, such as on existing structures, can be moved into installations to perform *in-situ* repair, and can share workspaces with other manipulators for hybrid manufacturing. The Norwegian company Fieldmade is developing such moveable container-based solutions. One of their systems is now active close to the Johan Castberg oilfield, run by Equinor. Furthermore, the German company LaserCladding GmbH is actively servicing ships and cranes through laser beam robotic DED at the Hamburg docks.

For AM processes where the material solidifies quickly after depositing, such as MEX with plastic filament, overhangs can be created without support material by reorienting the tool with respect to the build surface. This has the potential to reduce material usage and construction time. For welding processes, the ability to orient the tool ensures that the filler wire can be positioned ahead of the tool path.

The added freedom of the serially linked revolute joints also introduces added complexity. Cartesian manipulators will have a convex build volume (with respect to linear position), meaning that any straight path in the build volume is a straight path in the joint space of the manipulator. For industrial robot arms, the straight path may pass near a kinematic singularity and result in unreasonably large joint velocities, or the task space of the robot may not be convex because of the specific kinematic topology or due to joint limits [13]. This means that a toolpath may have to be verified for the specific kinematics of the manipulator setup before execution. Industrial robot arms also tend to prioritise positioning accuracy, which is achieved by having high joint and link stiffness, resulting in a high arm mass relative to the tool [14]. This means that sharp corners and rapid changes in acceleration may be more difficult to achieve than in other kinematic structures where there is less mass situated close to the tool.

Robot motion study

One of the main parameters of any additive process is the traverse speed (i.e., travel speed) of the nozzle. Therefore, the difference between the actual speed and the set-point speed was studied experimentally using a Meltio engine build head [15] mounted on a KUKA IONTEC KR 70 R2100 robot [16].

To verify the actual traverse speed and location accuracy of the experimental setup, the movement of the robot was recorded with a Leica Absolute Tracker AT960-MR laser tracking system, where 10 points in space were measured per second during robot movement. The location and velocity accuracy were determined from these measurements. The experimental setup is shown in Figure 10.2. Note that the laser reflector is mounted to the wire nozzle under the build head to ensure that the measurements reflect actual nozzle movement.

The robot was found to round all sharp corners and reduce the traverse speed through the corners, as shown by Figure 10.3a, where the x and y coordinates from one layer of a script for building a cube have been plotted with speed shown as a grayscale highlight for each point. The set traverse speed was 10 mm/s, and a reduction down to 6–8 mm/s is observed for most of the sharp corners.

In addition to a reduction of traverse speed, the corner rounding also resulted in considerable gaps between the perimeter line and the infill lines, since the infill lines would bend apart towards the perimeter, leaving a gap between the three lines. This has also been observed by metallographic examinations, where porosities have been found in this exact location, as shown in Figure 10.4.

The traverse speed was found to vary by approximately 30–40% across the entire range of relevant traverse speeds for AM, 5–15 mm/s, as shown by the last subplot in Figure 10.5. An interesting note is that the robot was able to move through curves with a speed of 11–12 mm/s when the set speed was

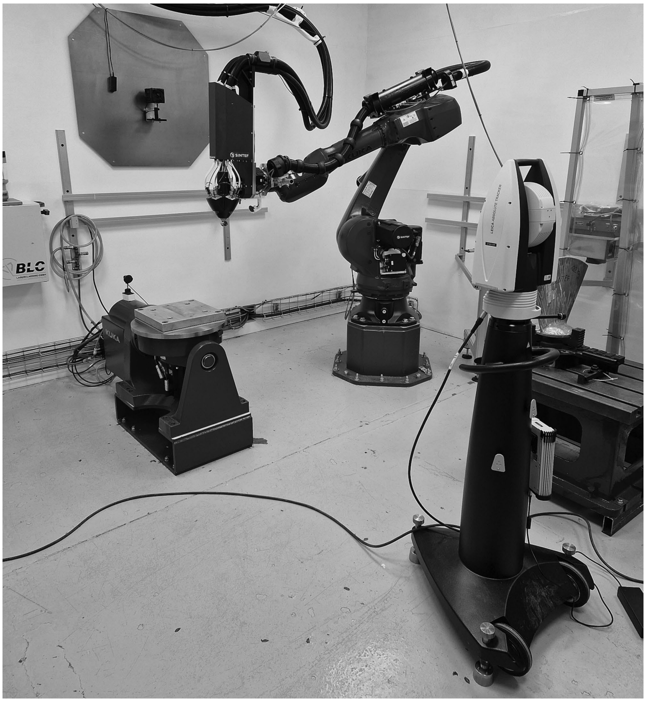
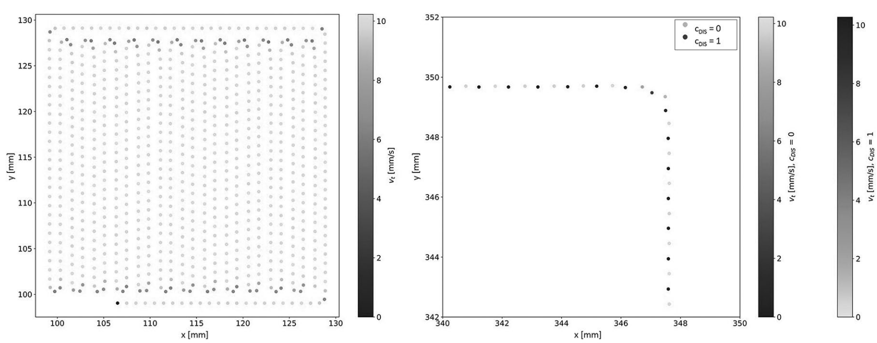


Figure 10.2 Experimental setup for robot motion study.



(a) Plot showing a complete base layer of a standard 30x30 mm cube

(b) Plot showing two paths around corner of cube perimeter for two different c_{DIS}-settings. Note how c_{DIS}=0 slows down the traverse speed slightly more, while still producing a rounded corner.

Figure 10.3 Plots showing robot movement in the xy-plane with traverse speed described through grayscale plots.

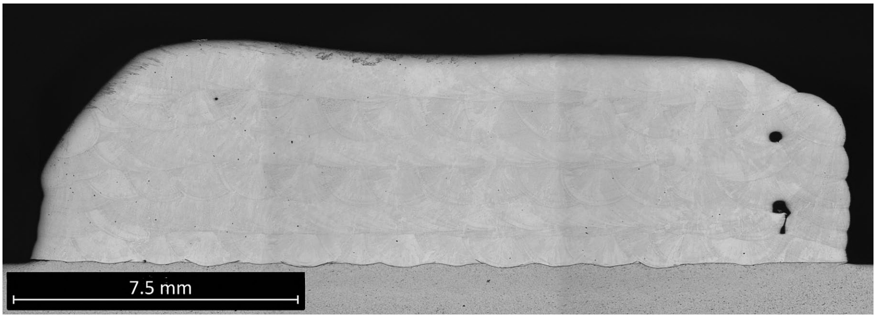


Figure 10.4 Microstructural imaging showing porosities in the finished build originating from a gap between perimeter and infill movement.

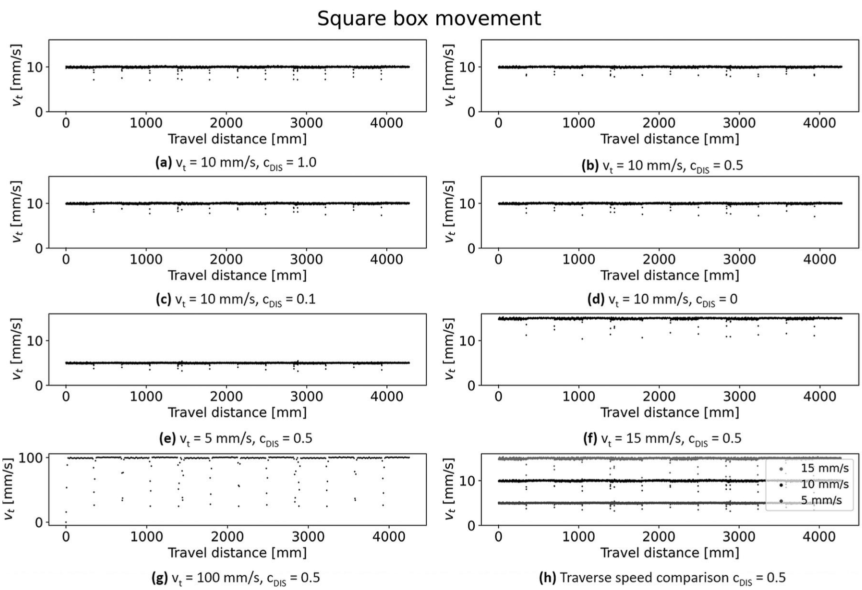


Figure 10.5 Profiles showing variations in traverse speed with different blend zone lengths and different traverse speeds.

15 mm/s but was still not able to keep a constant speed of 5 mm/s, since the same percentage-wise reduction of speed is observed also for 5 mm/s. This indicates that there are software limitations in the robot control system that produce these speed drops, not the physical ability of the robot.

The blend zone, or C_{DIS}, is a parameter that is defined in every robot programme written in KRL (Kuka Robot Language). It defines how far ahead the robot is allowed to adjust its trajectory for speed optimisation, meaning that a bigger C_{DIS} should result in more stable speed at the cost of reduced position accuracy around corners. It can be observed from subplots (a) to (d) in Figure 10.5 that the traverse speed reduction is almost identical for all the tested C_{DIS}-values. Setting the blend zone to 0.0 mm was expected to result in a full stop at the corners of a square movement due to the practical limitations of robot acceleration. This, however, did not happen, supporting the hypothesis that the robot controller overrides some of the programmed limitations of the robot. This is further supported by close studies of corner rounding with different blend zone sizes. Figure 10.3b shows that varying the blend zone from 0 to 1 mm has a very limited impact on the corner radius.

The findings give rise to a couple of considerations for AM applications:

- Consider real-time synchronisation of robot motion parameters and AM process parameters, e.g., wire or filament feed, electrical current (GMAW/GTAW processes), or laser power (laser-based AM processes). Such synchronisation can compensate for deviations in robot movement, but a more important aspect, beyond the motion study, is to improve the quality of the deposit and geometric accuracy by allowing additional material feed at unsupported external surfaces and other areas where constant parameters typically result in rounded edges and other deviations. Likewise, material feed and energy input can be adjusted to avoid accumulation in overlapped areas.
- Avoid the use of perimeters in path planning if possible. Since the rounding of corners may result in porosities between infill and perimeter, it may be better to not build with perimeter so that this problem is avoided.
- It has been shown that the robot will always round corners to a certain degree, meaning that fully sharp corners cannot be achieved. This is not a major limitation since a slight rounding can often be favourable to avoiding stress risers and other detrimental effects from sharp corners in the component design. Regardless, it must be considered in the design of parts that will be built with robot-mounted AM equipment.

Possibilities for industrial applications

Over the last decades, the interest in using AM to produce both prototypes and end-products in a near-net-shape has grown rapidly, and with it, the need for building larger components at a higher speed using these methods. We have seen a substantial increase in the use of robots for AM in the last five years. The Dutch company MX3D completed a 12.2-m walking bridge in Amsterdam in 2019. The bridge was made solely by their robotic WAAM system and got a lot of attention worldwide. Her Majesty, the Queen of Holland, opened this 6-tonne architectural wonder that is supposed to hold 20 tonnes. In the US, however, a company called Relativity Space has started testing the use of robotic WAAM to make 33.5-m space rockets.

Table 10.1 Important standards and guidelines related to specifications of AM parts [17]

Standard or guideline ID	*Description*
ISO/ASTM 52900 and ISO 17296-2	Standard terminology in AM process specification
DNV- CP-0267	Additive Manufacturing (AM) – approval of manufacturers
DNV- CP-291	AM feedstock
DNV- CP-B203	The qualification of parts made by AM for the oil and gas and related industries. Purchase, quality management, and manufacturing of parts.
DNV- CG-0197	AM – qualification and certification process for materials and components
API 20S	Additively manufactured metallic components for use in the petroleum and natural gas industries
ISO/ASTM FDIS 52943-2	AM of metallic parts with directed energy deposition in the aerospace industry.
ISO/ASTM 52901	Requirements for purchasing parts made from AM and guidelines on what information are to be exchanged between the customer and AM supplier
ISO/ASTM52907	Methods for characterising metallic powder
ISO/ASTM52910	Requirements, guidelines, and recommendations for using AM in product design

In the Norwegian industry, Westad Industri has been an early adopter in creating high-performance butterfly valves for the offshore industry by making surface claddings applied by a robotic DED system using laser and powder.

SINTEF Manufacturing also has a large robot cell with a multi-laser DED system, applying both wire and powder. SINTEF sees these types of metallic systems as an improvement over single laser systems as they are more stable, have fewer environment, health, and safety problems, and can produce parts relatively faster without spatter.

As discussed, the use of robotic systems for AM is seen as well-suited for large-scale parts and gives high flexibility for control. However, there are challenges mentioned in this book chapter that need to go into consideration for optimal process stability and part finish.

Table 10.1 lists the relative standards used for purchasing, setting requirements, and certain recommendations for AM parts ordering. However, in many sectors, components need to be classified and certified by the appropriate class society dedicated to the intended application area. Det Norske Veritas (DNV), for instance, is one such class society dedicated to the marine and offshore industries. Based on the guidelines, manufacturers become certified/approved for AM production according to the DNV guidelines and can achieve approval for manufacturing components with given materials after documenting their achieved properties.

Robot path planning for AM processes

In this section, we discuss robot path planning for AM processes. A robot path is a set of points or curves in the joint or operational space that the robot follows during the execution of motion [18]. The robot path is executed by the robot controller using firmware-specific velocity and acceleration profiles. Here, we consider path planning as an offline procedure, where the robot path is generated for the entire AM task before task execution starts.

Aspects of robot path planning for different AM processes

A pipeline for an AM process is shown in Figure 10.6. This is a general representation covering a conventional AM process [19]. In this section, we will concentrate the discussion on the steps closely related to path planning. Once the part to be produced is modelled in a computer-aided design (CAD) programme, it is converted to a sliceable representation, such as a stereolithography file, where the part surface is discretised by triangle elements. This way, a part can be intersected by a plane, creating one or more closed polylines. The process of obtaining the polylines by intersection of the sliceable part with multiple parallel planes is referred to as slicing. The next step is path planning, where planning parameters and the set of polylines are used to form tool paths. Path planning varies depending on the AM process, material, software capabilities, and desired results. For example, for the polymer MEX process, it is common to have to path planning sub-steps: path planning for outer and inner walls based on parameters for the number of perimeter shells, and path planning for filling the material between the walls based on the chosen infill density and desired infill pattern. The tool path planning also plans tool control such as start/stop of material feed or extrusion rate. The next step is the generation of robot instructions. In this step, the points of the planned path are converted to a list of high-level commands readable by the robot controller, such as G-code or a native robot input language. Once the list of robot instructions is generated, the robot controller can execute the motion and control the AM tool. Post-processing, for example, to remove support material, may be required depending on the AM process and the part design.

Path planning is highly dependent on the process involved. For example, the welding methods used within WAAM all have in common that the arc

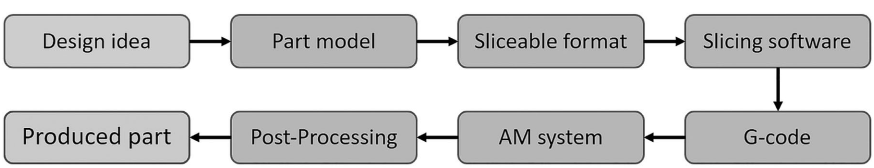


Figure 10.6 Typical pipeline for an AM process.

initiation and flame-out, i.e., the starting and stopping of the welding process, lead to uneven material deposition [20]. As material is therefore deposited continuously, the planned path should not cross its own path within a planned layer, as this could lead to a heap-up of material. Sharp turns can also be challenging depending on the movements of a robot manipulator, as the material flow is separate from the robot movements, and a lower movement speed will lead to more material being deposited over a given distance. The starting and stopping points of the build are generally challenging for many AM methods.

As part of the PhD work in SFI Manufacturing, several thin-walled structures with intersections and overhangs were built using WAAM [21]. These structures were all built using offline control of the robot's path, with some manual adjustments of the welding parameters during the welding process. Early experiments were done investigating how corners and transitions between layers could be solved for a continuous and automated WAAM process. Specifically, cold metal transfer (CMT) welding was used, which is a very stable and spatter-free type of GMAW with heat input in the lower range of GMAW techniques. The early experiments showed that, in line with the robot motion study presented earlier, sharp corners were challenging. As the material deposition rate remained the same while the traverse speed was reduced in corners, material would accumulate in those areas. The effect was reduced by using rounded corners in the part design.

Similarly, the transitions between layers for a continuous building process were solved by having a smooth increase in the vertical position of the tool over several centimetres when transitioning to a new layer. Increasing the vertical position of the welding gun at a single point was also tested, but while keeping a constant rate of material deposition, even an increase of only a couple of millimetres created a delay large enough to cause a significant heap-up of material at a single point along the path. This would accumulate for each passing layer, eventually causing large deformations in the structure. Experiments were also done to investigate how the path could be planned to avoid intersections within a layer, as this would lead to double deposition of material at the point of intersection. If stopping and re-starting the welding process are to be avoided, to steer clear of the issues related to arc-initiation and flame-out, this is something that should be considered. By instead designing the path to include opposing angles positioned so close together that the metal would melt together, it was possible to recreate "intersections" in the pattern of each layer without having the tool cross its own path. One such structure can be seen in Figure 10.7, and full details on these builds can be found in [22].

A framework for set-based control of the joints of a 6-DOF robot manipulator was also tested for thin-walled WAAM structures [23, 24]. This method is meant to simplify the movements of the robot manipulator by defining the position and/or orientation control of the end-effector to stay within a given set rather than at a specific value, and the idea was that this could be used to create a smoother building process for WAAM. The structure was a cylindrical structure with a continuous, helix-shaped path, and the set-based constraints were set to allow for a small deviation away from a vertical orientation of the tool, i.e., orthogonally onto the substrate [25]. Because the change in orientation of the tool was not symmetrically distributed around the circular structure, even a very small difference in the orientation (approx. 6°) led to a significant variation in how the material was deposited and accumulated as the building process progressed. The conclusion was that for WAAM, the orientation of the tool impacts the build too much for the set-based control framework to be a suitable method of control, and it was clear that the orientation of the tool is a significant part in the robot path planning.

The structure shown to the right in Figure 10.7 was also built using CMT, with continuous material deposition along an upward spiralling helix path with a continuously increasing radius, thereby creating an overhang. This could have been solved using a *mobile* building surface around a *fixed* point of material deposition, as demonstrated by [26] and [27], and this seemed to be the dominating approach at the time. However, if the building surface could remain fixed with a mobile and flexible point of material deposition, it could be possible to use the technique in a more practical scenario, as discussed further in [21]. In an industrial context, this could, for example, allow for repair work on ships or other large structures that cannot easily be moved or tilted around a fixed nozzle. So, by having the orientation of the welding gun follow the angle of the increasingly tilting wall, it was possible to create such an overhang without the need for support structures. The final angle was approx. 43 degrees, and future work should investigate how prominent such an overhang can become before the structure starts showing significant deformations. More details on this can be found in [28]. Future work should also focus on real-time monitoring of the building process as well as feedback control of the robot's

Figure 10.7 Structures with overhang and intersections built using WAAM.

path. Combining these could improve the quality of the build by adjusting the path of the robot to compensate for deformations during the build.

In the case of using GTAW, an additional degree of freedom about the welding gun axis must be taken into consideration. This is due to the wire must be fed in front of the weld arc along the path. In a robotic setup without a rotary table, this can restrict the execution of certain continuous paths, as the wrist joint of the robot has rotational limitations. An illustrative example of that could be a continuous coil-like path for building a thin-walled cylinder. To execute such path, a rotary table for a workpiece is mandatory.

Path generation on non-planar surfaces using CAD models

Many commonly used AM methods are based on gantry systems with a fixed building direction, and the planned layers for the manufacturing process are therefore also planar and perpendicular to the preceding layer. This pipeline then follows the typical pipeline for AM as presented in Figure 10.6. Allowing for curved layers could greatly improve the flexibility of the AM process and make it possible to construct geometries that would otherwise need additional support structures. In the following sections, two path planning methods to enable printing along non-planar layers are presented.

To enable path planning along non-planar layers, a method based on the CAD model in the STEP format was proposed by one of the master students in SFI Manufacturing. While the STL format contains an approximation of the surfaces of an object, the STEP model contains an accurate description of the surfaces. This method only considers the faces of the CAD model, where a face is a surface bounded by a set of edges. The method consists of two main steps: sampling the desired surface into a point cloud and generating the path based on the points.

The surface is parametrised by a system based on curvilinear coordinates. These coordinates are used to sample the surface by iterating through them with a given step length. The sampling is gathered in a one-point cloud. The results of the sampling on two different surfaces can be seen in Figure 10.8. The next step is to generate the path based on the point cloud. Three different

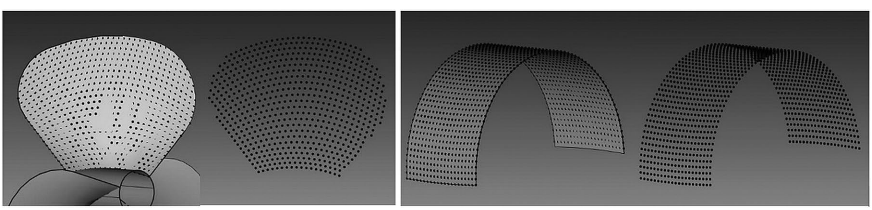


Figure 10.8 Resulting point cloud from sampling a propeller blade and bridge [29] (CC BY-NC-ND 4.0).

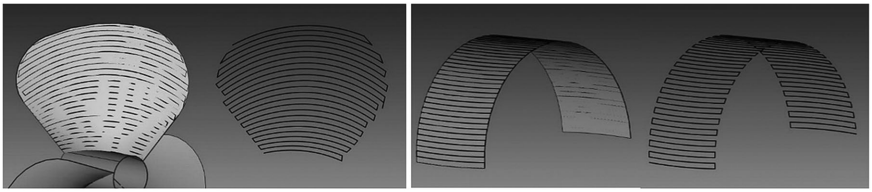


Figure 10.9 Path generated using the weighted greedy algorithm [29] (CC BY-NC-ND 4.0).

algorithms for generating the path were tested, including a solver for the Travelling Salesman Problem, greedy choice, and weighted greedy choice.

The path generation method was tested on two different CAD models: a curved rectangular surface resembling a bridge and a propeller blade. The bridge was chosen to demonstrate how a path for printing in overhang can be achieved, and the propeller blade to demonstrate printing along nonlinear paths. The result of the path generation using the weighted greedy algorithm can be seen in Figure 10.9.

The sampling algorithm captured the geometry of the surface well. Both surfaces were captured with a constant step length. For more complex geometries, a shorter or varying step length step length could be appropriate. Out of the three different algorithms that were tested for path generation, the weighted greedy choice gave the best results. Results from the other two algorithms can be seen in [29] and [30]. The paths generated with the weighted greedy algorithm show how non-planar paths can be realised using a 6-DOF robot manipulator.

Path planning for curved layers

Many commonly used AM methods are based on gantry systems with a fixed building direction, and the planned layers for the manufacturing process are therefore also planar and perpendicular to the preceding layer. Allowing for curved layers could greatly improve the flexibility of the AM process and make it possible to construct geometries that would otherwise need additional support structures. A framework for performing robotic AM using a 6 DOF robot manipulator was proposed by Dai et al. [27], aiming to decompose arbitrary objects into manufacturing layers and then automate toolpath generation for multi-DOF AM. The methods suggested by Dai et al. have no constraints on the shape of the generated manufacturing layers, allowing for curved layers, as well as planar ones.

Two of the algorithms suggested by Dai et al. [27] were implemented and tested using simulations by one of the master students in SFI Manufacturing in 2019 [31]. Based on a digital model, a discretisation process divides the continuous volume into a final number of voxels before accumulating these voxels into printing layers. A tool path is planned for each layer, which can then be translated into machine instructions before executing the build process itself. The scope of the master's project mainly covered 2D objects. After using 2D objects to refine and understand the algorithms, tests were done on one 3D object, as the methods suggested by Dai et al. were designed for 3D objects as well [27].

The algorithms were tested on six different input objects, all with different overhangs. The method tested in the thesis was greedy growing convex front advancing (GCFA), with and without incremental shadow prevention (GCFA-ISP). The GCFA algorithm processes each voxel locally, accumulating them into a sequence of manufacturing layers in a bottom-to-top manner. As the methods suggested by Dai et al. had no constraints on the shape of the layer, curved layers were also generated [27]. Additional constraints ensured a self-supported and collision-free manufacturing process. A weakness of the greedy strategy is that it will always go for the locally optimal choice, which might create challenges later in the manufacturing process. The improved GCFA-ISP scheme introduces an additional constraint to avoid shadowing, i.e., reduce the number of voxels that cannot be included in current or future building layers due to their position compared to already planned layers, as shown in Figure 10.10.

The algorithms were reviewed and altered to generate satisfying and realisable results from the simulations. Building without support structures was enabled by reducing the number of neighbouring voxels eligible for being accumulated into the next layer. The altered GCFA-ISP algorithm was stricter, ensuring that, before adding a voxel to the next generated layer, this voxel must cause the shadowing of *less* voxels compared to the greedy scheme. The methods for curved layers were also compared to an existing object decomposition method [31]. The results from the master's thesis showed that the platform size impacts the generation of the layers and that a larger surface can lead to more voxels being shadowed. For all the tested structures, the results improved for curved layers compared to planar layers when considering the number of voxels that were missed when generating the path for each layer. This shows how a manufacturing process can benefit from the flexibility provided by a 6-DOF robot manipulator with the ability to deposit material at a non-vertical angle. For more details, see [27, 31].

Robotic AM using commercial CAM software

Hardcoding the robot's movements for complex parts can be quite complex and time demanding. Just as in a CNC-machining operation, CAM software is used to programme plan and programme the code that executes the build job. Hence, the software has an input of CAD design and an output of G-code, as described in Figure 10.5. There are several available CAM software packages that are applicable to robot-controlled AM. Most of these

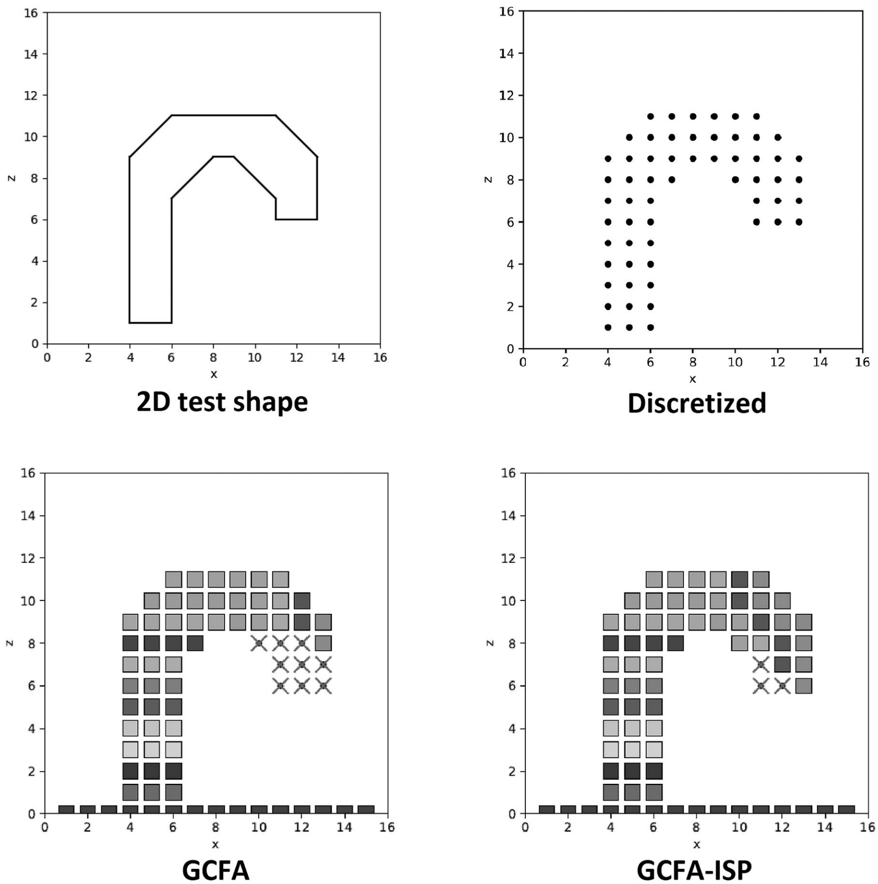


Figure 10.10 2D test figure with overhang. Using the improved GCFA-ISP algorithm reduces shadowing [31].

are derived from machining, e.g., SKM DCAM, ModuleWorks, Robotmaster (Mastercam), Siemens NX, Catia, SprutCAM, and Grasshopper.

Vision sensor technology for robotic AM processes

The integration of sensor technology in the field of AM is essential for the assessment of 3D geometry and the optimisation of the production process. The sensors allow for continuous monitoring and control of various stages of the AM process, helping to ensure the process's repeatability and consistency with the final product. For instance, measuring the height and shape of the deposit during the build process can provide valuable information to make adjustments and improve the geometric accuracy of the final product. In addition to 3D geometry evaluation, real-time monitoring of process parameters, such as the temperature of the melt pool, can help maintain the desired process conditions to achieve acceptable material quality [32]. The use of robot manipulators in AM presents the opportunity for an increased building volume and an expanded degree of geometric complexity compared to traditional cartesian machines. Despite these advantages, it also raises the likelihood of deviations occurring in the manufacturing process, as robot manipulators typically have good repeatability but lower geometric accuracy. Previous research has shown the potential of using different camera technologies and customised vision-based setups in AM processes [33]. Integrating sensors into industrial MEX systems is a vital area of research, which involves the development of advanced sensor concepts for high-temperature and large-volume environments and efficient sensor modules that can function within the constraints of moving machine parts and frame structures [34]. With these advancements in sensor technology, manufacturers will be able to more effectively monitor and control the AM process, ensuring a consistent and high-quality final product. In the following, a brief introduction to optical measuring techniques for in-process assessment of geometric deviations is given.

Profile laser scanning

Profile laser scanning is a non-contact, non-destructive measurement technique that is widely used in various industrial applications. By projecting a laser beam onto an object and capturing the resulting light scattered from its surface using a camera, the three-dimensional geometry of the object can be extracted by image processing techniques (Figure 10.11). The working

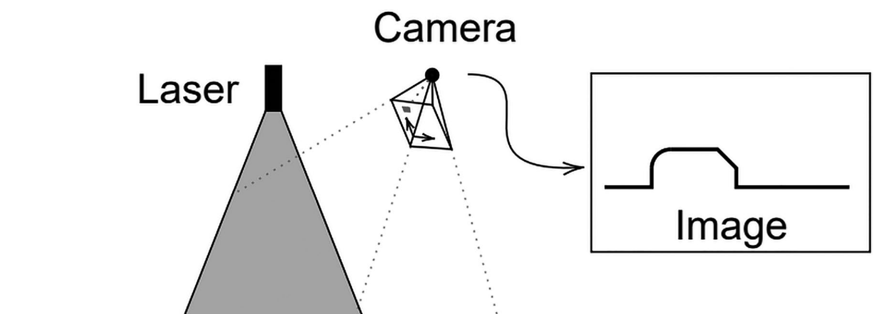


Figure 10.11 Working principle of line laser scanners.

principle of profile laser scanning is based on triangulation, a fundamental geometric principle that involves determining the position of an object based on the intersection of two lines. In profile laser scanning, the laser source and the camera are positioned so that the laser beam and the camera line of sight intersect at the surface of the object being scanned.

The distance between the camera and the object can then be calculated based on the position of the laser beam in the camera's field of view. Profile laser scanning is a fast, efficient, and accurate method of measuring objects and surfaces. Line-profile laser scanners can be used for dimensional measurements of parts and assemblies, quality control, reverse engineering, and 3D scanning. One of the critical applications of line laser scanners in AM is the detection of defects and imperfections on the surface of the printed part. A reconstruction of item surfaces can be done using a line laser scanner quickly, inexpensively with excellent accuracy. Moreover, this only requires a single camera and a single laser light beam to be projected at a fixed angle from one another. A single point cloud is created from all the collected profiles as the item is repeatedly profiled as it passes past the laser line scanner. The accuracy and precision of profile laser scanners depend on various factors, such as the laser source intensity, the camera resolution, and the environmental conditions. However, with advances in laser and camera technology, profile laser scanning is becoming increasingly accurate and reliable, making it a valuable tool for industrial AM applications. The line laser scanner helps identify the cause of defects. By analysing the structure of any manufactured part, the scanner can detect any issues in real-time manufacturing processes and the potential to correct them, resulting in fewer failed manufactured parts and increased efficiency. These kinds of technologies have the potential to integrate with different AM systems and provide a better diagnostic of the structure of manufactured objects as well as the capability to identify deviations in active production processes.

3D cameras

3D imaging is a non-contact, non-destructive measurement technique increasingly popular for capturing and analysing the shape and texture of objects in three dimensions, providing more comprehensive information than traditional 2D vision. Various types of 3D cameras are available, including structured light cameras, time-of-flight cameras, and stereo cameras. In stereovision, two cameras are positioned at different angles to capture the same scene. These cameras work together to triangulate the depth of objects within the scene and generate a point cloud, a 3D representation of the scene. Structured light cameras combine a projector with a camera to project and image a known pattern, such as grids or horizontal bars, onto a scene. The depth of objects in the scene can then be determined. The principle is illustrated in Figure 10.12. Time-of-flight 3D cameras measure depth by evaluating the time it takes for a light pulse to travel to an object and return.

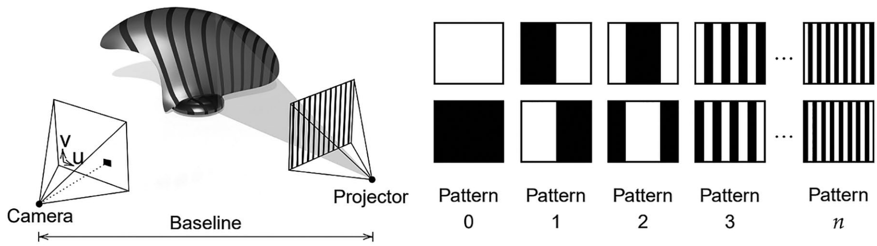


Figure 10.12 Left: Structured light imaging principle. Right: binary structured light patterns which are successively projected onto the object.

3D cameras are becoming increasingly important in the manufacturing and inspection processes, as they can provide detailed information on the geometry and shape of products, improving production accuracy and consistency. 3D cameras are also helpful in other robotic and automation systems, as they provide real-time information on the position and orientation of objects in the environment. The term *point cloud* refers to a group of data points in three dimensions that are often generated by a laser scanner or other sensor. Point cloud data can be utilised to construct a digital model that can be employed in the AM process by capturing the geometry of an object. Making a digitised representation of an existing component and utilising the representation to manufacture a copy using AM is one manner to use point cloud data in AM. Making duplicates of unique or challenging-to-manufacture products or generating replacement parts for machinery or other equipment can benefit from this. Another way to use the point clouds generated from the sensor is to utilise the data to increase the accuracy of the AM process by comparing the finished product's quality to the original design. One way to determine if any deviations or mistakes were made during the manufacturing process is to compare the final product's point cloud data to the original design's point cloud data. Such comparisons can assist in finding and fixing problems early on, enhancing the finished project's overall quality.

Thermal cameras

Thermal cameras play a valuable role in AM by providing insights into heat-related aspects and can be used for monitoring and controlling the AM process. These cameras capture images in the infrared radiation spectrum and estimate the temperature of the objects within their field of view.

Thermal cameras are beneficial for monitoring the temperature of the melt pool, as it is an important parameter affecting the final product's quality. By monitoring the melt pool, one can determine the melt pool size, shape, temperature, and solidification rate, among other things. The use of thermal cameras enables the detection of anomalies and deviations in the manufacturing process, helping to identify potential sources of defects and improve the consistency of the final product. For example, suppose the temperature of the melt pool is higher or lower than the desired range. In that case, thermal cameras can detect the deviation, and the process parameters, such as the heat input and travel speed, can be adjusted to maintain optimal conditions, reducing the risk of manufacturing defects such as porosity and cracking. In metal AM processes such as WAAM and DED, thermal camera temperature estimates can be used to maintain a desired interpass temperature between the layers or beads, avoiding defects such as excessive hardness. In addition to monitoring the temperature of the melt pool, thermal cameras can also be used to monitor the thermal behaviour of the build platform, the cooling system, and the heating elements, which are critical components of the AM process.

Feedback control for AM processes

Although closed loop control is currently being used in AM, both for cartesian machines and robotic manipulators, it is almost exclusively used for ensuring that the print head or deposition tool follow the pre-designed reference trajectory. The concept of utilising feedback control for supervising or directly controlling the shape or quality of the build during production is a largely unexplored idea, both in literature and industry. This type of feedback control can be envisioned as an outer control loop in an AM system, where the usual robot control system constitutes the inner loop. The concept is illustrated in Figure 10.13. The literature review [35] explores this topic and divides it into three areas: geometric error detection and correction, deposition process control, and thermal monitoring for layer scheduling and cooling control. It is concluded that, in addition to control design, advances in measurement and sensing for feedback and in 3D reconstruction are needed for realising this concept. The main difference from the classical AM process in Figure 10.6 is that in Figure 10.13, sensor measurements are used as control feedback to improve the quality and geometric precision of the produced parts.

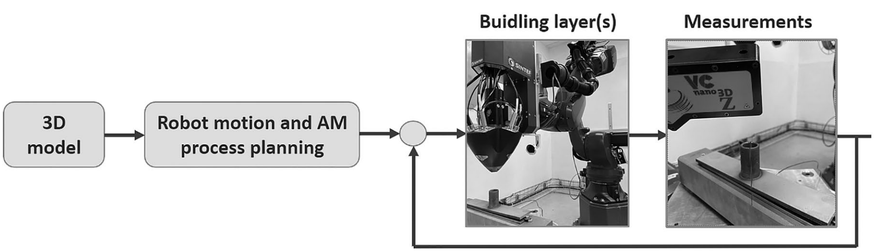


Figure 10.13 The concept of feedback control in AM processes.

Conclusions

We have presented a review of the work on utilisation of robotic manipulator arms for AM processes done in the SFI Manufacturing project. The review was limited to DED and polymer MEX AM processes, where two variations of DED were discussed: laser melting and wire-arc AM (WAAM).

Generally, Cartesian manipulators are the dominant robotic platform in industrial AM implementations. Serially linked robotic arms can provide greater flexibility to the process, e.g., due to the possibility of varying tool orientation, but introduce additional complexity due to the transformation from joint to task space. Robotisation of AM processes might also require synchronisation of AM processes and robot motion parameters to increase quality and reduce geometrical deviations.

From the perspective of industrial implementations, the cost of equipment might be significant; however, the classification and certification of AM produced parts is a more critical problem. We have provided a table with several relevant standards and guidelines.

Classical path planning for AM processes is industrially done using CAM software. It might work well for standard cases; however, path planning with overhang and path planning on curved surfaces is still an open research field and is of little use in industry.

Sensor data can be beneficial for AM processes. We have provided application examples of profile laser scanners and 3D cameras for geometry quality control both at the bead and entire part level. In addition, thermal cameras can be used for parameter monitoring of melt pools in DED processes, which allows for early defect detection.

Finally, we have provided some insights into possibilities for feedback control for AM processes. Such process control can provide significant benefits for the improving quality and geometric tolerances of products and should be more researched in the future.

Declaration

The authors declare no competing interests and confirm that the manuscript has been read and approved for publication by all named authors.

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Chapter 11

Sensor-guided motions for manipulators in manufacturing

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Introduction

Industrial manipulator arms have traditionally been used for highly repetitive tasks due to their excellent precision, speed and endurance. Examples of industrial applications include welding, palletizing, assembly and disassembly, pick and place, and spray painting. Many of these tasks are carried out by pre-programming the arm to move through a sequence of configurations without any knowledge of the environment. Today, manufacturing faces higher demands in meeting increased customization. A central challenge within robotic manipulation is therefore generalization, e.g., a bin picking system that can be automatically customized for specific objects. This requires external sensing. The idea of integrating sensors is far from new. The Stanford arm, a 6 degrees of freedom (DOF) electrically driven arm with force-torque sensing, was created in 1969, whereas Automatix introduced the first arm with built-in machine vision in 1981 [1]. Sensors and sensor systems have developed from being purely mechanical, to electrical, to advanced electronic sensors, until today's smart sensors. The latter have enhanced performance, better integration, multi-parameter sensing, self-configuration, self-calibration and self-repair capabilities [2]. A classification of literature with respect to sensor modalities (distance, vision, touch and audition), control objectives, target sectors and types of robots can be found in [3]. Recent advances in sensing, together with increased computational power in more compact formats, as well as the developments of new algorithms (e.g. the use of neural networks for machine vision), are further enabling industrial usage of sensor-guided motions for manipulators.

Some of the applications for sensor-guided motions are summarized here and will be studied in detail in the later sections:

- Handling unorganized environments, e.g., picking from bins. Keeping parts in bins is space-efficient, and storage space is often a limited resource in manufacturing.
- Interacting with moving objects with a not necessarily predefined speed, e.g., loading and unloading of overhead conveyor trolleys.

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- Assembly where, for instance, tolerance is smaller than the precision the robot cell is able to achieve in open-loop.
- Deburring and additive manufacturing processes, as well as glue dispensing [4], where the properties of the removed or added material cannot be sufficiently accurately predicted.

In addition, sensor-guided motions are highly relevant in human-robot collaborations and are considered an enabler of future manufacturing systems [5]. Sensors information can be used to estimate body posture, action intention, ergonomic risk, etc. in human-robot collaboration [6–9]. Finally, sensor-guided motions can also be a benefit for more traditional tasks. The use of sensor-guided motions can reduce the time and effort used for re-programming in small-batch productions, or the production of different shapes and sizes. In this chapter, we summarize some of the efforts on sensor-guided motions within robust and flexible automation in SFI Manufacturing. SFI Manufacturing is a cross-disciplinary center for research-based innovation for competitive high-value manufacturing in Norway, 2015–2023. Parts of this chapter are based on previously published works, and the main contributions are the overview of sensor-guided motions for manipulators in manufacturing and our recommendations for further research in these areas.

The chapter is organized as follows: The first four sections are focused on specific applications of sensor-guided motions we have investigated: 'Reactive control for assembly', 'Deburring of cast parts', 'Automatic loading and unloading of hanging trolleys', and 'Bin picking of reflective objects'. The last two sections are on two generic methods for planning and control: 'Nonlinear model predictive control for robot manipulator trajectory tracking' and 'Task-priority set-based reactive control'. For each section, we start with the motivation and problem description for our research, then provide our solution, before we finalize with conclusions and recommended further work.

Reactive control for assembly

Motivation and problem description

In the most general terms, assembly is a process intended to limit the relative motion possible between two or more parts. This is a combinatorically explosive process that can involve different edge or surface geometries, different materials, surface finishes, relative tolerances, fastening methods, and other attributes. The assembly process is composed of multiple steps, and generally, two parts or subassemblies are assembled to form a stable whole when the process completes. Each part must be moved by a free-space and potentially surface-interacting motion from some contact situation to a new contact situation.

Programming costs are a large part of the total cost of robotic automation. It is common to reduce the complexity of the programming by requiring a static collision environment, a fixed assembly process, a specific manipulator design, and robot-relative motions. This often results in either specific mechanical designs, e.g., compliant tools, or specific sensor-guided motions created for the robot setup. For low-volume product series, the relative cost of specialized tools and programs to the total profit is too small to merit automating the task. In an ideal scenario, programming the robots would be possible to integrate into the design stage of product development and would be as easy as using a CAD program. A *fully automated assembly system* software would be able to evaluate the automation potential of a design, specify requirements of the physical hardware, such as reach or sensing capabilities of the robot, and plan and execute the assembly task on relevant robot hardware.

A silver bullet applicable to all possible designs, capable of both analyzing designs, planning sequences and trajectories, and controlling the robots during execution, is likely impossible to create. Issues are, for example, that designs can be created that violate underlying assumptions, such as a cobra weave (a woven unstable toy made from ice cream sticks, as discussed in [10]), where none of the subassemblies will form stable wholes, that finding an assembly sequence even in the planar case is NP-complete [11], or that the specific hardware may have environment-related signal loss that degrades controller performance.

In SFI Manufacturing, the research goal was to investigate paradigms for such fully automated assembly systems, primarily focused on the following research topics:

- What sort of system architecture can facilitate a closer link between design and automation?
- How can nominal design information be used to automatically generate executable robot programs?

Solution

Arbo et al. [12] propose a system architecture that defines tasks in terms of the nominal CAD information and executes these based on a known set of workpiece-oriented skills that can be executed on different robot hardware platforms using the control layer. This splits the development effort of a fully automated assembly system into different modules that can be developed and improved separately. The proposed architecture, illustrated in Figure 11.1, is separated into three layers: an application layer where the user can annotate a CAD model with a set of assembly tasks from a task library; a process layer where the tasks are matched up with parametric robot skills and the process parameters are inferred from the nominal CAD information and robot cell

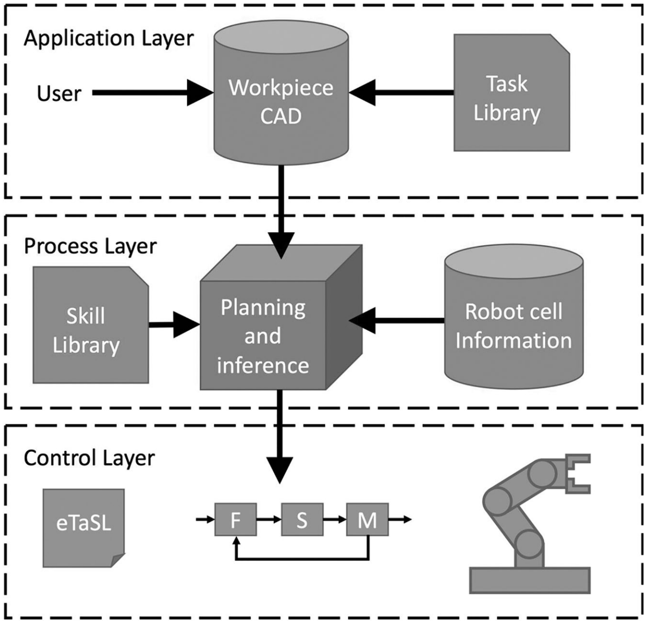


Figure 11.1 System architecture for an automated assembly system described by Arbo et al. [12]. Copyright obtained from Pane et al. [13].

information; and finally, a control layer where a finite state machine implementation of the skills with task-related transitions is executed on the robot.

The tasks annotated in the CAD software are abstract descriptions of the assembly task to be undertaken, e.g., insert or place, and are annotated between frames attached to the relevant features of the parts to be assembled. The skills are defined as either atomic or composed. Atomic skills are parametric descriptors of a motion operation, e.g., *guarded_move* denoting a movement operation where a transition is triggered when a force is detected or failure if the motion completes without any force detected, or *cylinder_insert*, where a compliant motion is used to perform peg-in-hole insertion with dithering depending on the tolerances involved. Atomic skills are implemented using the constraint-based programming paradigm eTaSL/eTC [14] and have a set of continuous inputs such as force measurement, continuous outputs such as distance error, and monitors for triggering failure or success events. Composed skills are finite state machines where each state describes the atomic skill or the nested finite state machine, and the edges describe the events that trigger transitions from skills. The constraints in the atomic skills are described by constraints between the relative DOF between feature frames on parts, e.g., the tip of the rotor and its housing, or the fingers of the gripper and the rotor. Supposing the constraint is that vector $\boldsymbol{d}_1$ on part 1 is parallel with vector d_2 on part 2, and that the robot is holding part 1 such that there is a known mapping from the joint angles to the vector d_1. Then the error from the constraint is

$$h(q) = \left\| d_1(q) \times d_2 \right\|,$$

where h is a scalar measure of the error and $q \in \mathbb{R}^n$ represent the joint angles. The constraint is realized in eTC as a regulation problem, and exponential convergence to the constraint is achieved by defining the Jacobian of the error as

$$\frac{\partial h}{\partial q} = \begin{bmatrix} \frac{\partial h}{\partial q_1} & \cdots & \frac{\partial h}{\partial q_n} \end{bmatrix},$$

and enforcing the controller

$$\frac{\partial h}{\partial q} \dot{q} = -Kh(q),$$

as a constraint to a quadratic programming problem that finds a $\dot{q}$.

This approach is closely related to the task-function approach of Samson et al. [15] and results in reactive joint velocity-resolved motions, but has support for simple task-prioritization by relative weighting of constraints, softening of constraints, and convergence of inequality constraints. Time or sensor information can be included in the constraints; see the original eTaSL/eTC article for more information [14]. A cornerstone of this approach is that the controller behavior, and thus the motion, is defined between the parts rather than directly in joint space or the end-effector frame of the robot. This means that different robot cell information can include different robot kinematics and still yield the same motion. Sensor-based skills are also transferable between robot cells, provided that the sensor signals behave similarly.

In the prototype system [12], the task specification with CAD information was serialized as json files from the application layer to the process layer, and each task had a single associated composed skill. The process layer populated the lua code specifying eTaSL skills, and the control layer executed the state machines of eTaSL skills on the robot. The prototype was demonstrated on the problem of assembling a screw compressor using a KUKA (www.kuka.com) LBR iiwa 14.

The system architecture was extended by Pane et al. [13] to simplify task annotation to only annotating relevant CAD constraints between the parts. The extension allows tasks to be annotated in FreeCAD (www.freecad.org) as CAD constraints between topological primitives that define the relevant interacting faces. The constraints are interpreted using an ontology to

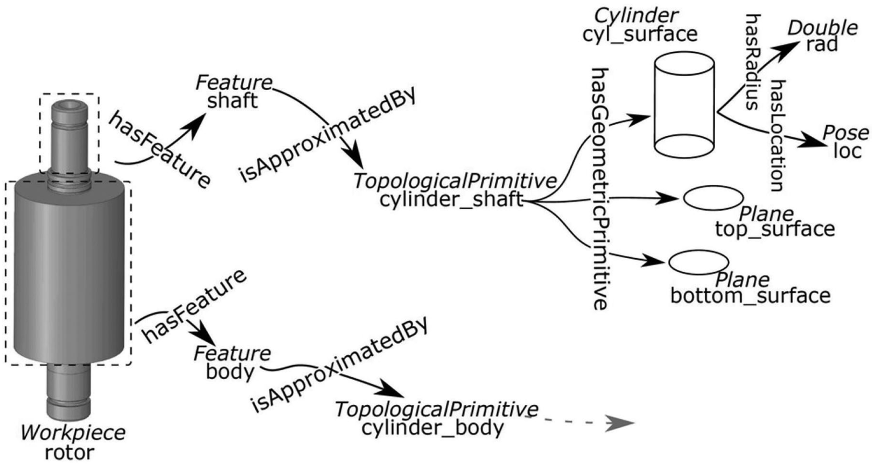


Figure 11.2 Modeling of the CAD part, feature, and nominal geometric primitives. Copyright is obtained from Pane et al. [13].

describe the relation between the part, feature, and its nominal geometric primitives, as illustrated in Figure 11.2. A relational model is also created to describe the relation between the task and its constraints and motion defining skill constraints (see Figure 11.3). For the CAD constraints implemented, a corresponding kinematic constraint and the relevant wrench constraints that this induces between the parts are described. The ontology-based skill selection allows the architecture to 'ground' the task in a specific skill based on which constraints are present in the annotated task and which constraints are defined for the skill. This inference is primarily for defining the reactive sensor-feedback-controlled motion required during the assembly. The composed skill for a single assembly would include information such as where the part is in the work cell, which tool to grasp the part with, the kinematic structure of the robot, etc. The suggested extension was demonstrated on the same compressor assembly using a KUKA LBR iiwa 14 robot, as in the article by Arbo et al. [12], and on a motor assembly case using a KUKA KR16-2 robot.

As there are many different CAD software vendors with differing interfaces, Mohammed et al. [16] investigated using the STEP AP242 neutral exchange file format to extract the motion constraints. STEP AP242 is defined in ISO 10303-242:2014 and provides assembly constraints such as:

- Specifying a part as a fixed constituent in an assembly,
- Parallel relationship between mating features,
- Coaxial relationship between mating features, etc.

The assembly constraints are defined between features of geometric entities, and the article provides a procedure for extracting the constraint information

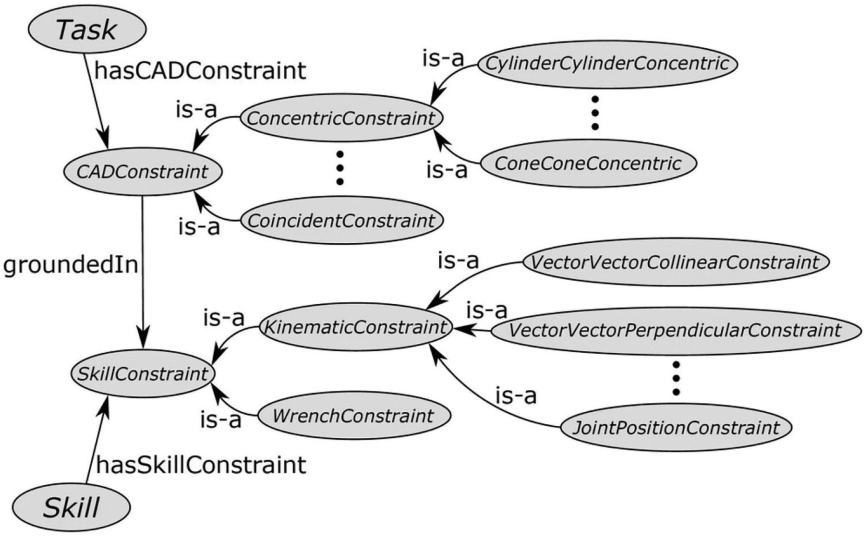


Figure 11.3 Relational model between tasks and the constraints they define between features in CAD and skills and the constraints required to define reactive motion controllers. Copyright is obtained from Pane et al. [13].

and defining relevant coordinate frames. The constraints are used directly to specify the relative motion constraints of the parts, as the assembly constraints should form a full positioning requirement for the part relationship. It is noted that the different gains for the regulation controllers of the constraints can be tuned to create different motion behavior of the parts. To ensure that the parts do not collide for different initial starting conditions, it is suggested to either use a different controller formulation or to sequentially include constraints while maintaining collision avoidance constraints such that the motion may converge to the assembly state without collisions. The use of STEP AP242 constraints directly as motion constraints was simulated for a motor assembly use case using a KUKA KR 6 Agilus robot.

Conclusions and recommended further work

The work in SFI manufacturing suggests a system architecture that has three main aspects: a workpiece-centric task specification, transferable sensor-based skills, and direct annotation or extraction of constraints from the nominal design. The workpiece-centric task specification separates the specification of what the assembly is supposed to achieve from how it is supposed to be achieved. This means that there is an opportunity for a designer to inspect the motion without knowledge of the robot system, and the robot system can be changed without redefining the motion required for the assembly. As assembly requires moving one or more parts to a new contact situation, there is also a need for the skills that achieve the motion to react to sensor input. This is essential for peg-in-hole insertions or screw operations where both jamming and destruction of screw threads may occur. Simply placing a part on a surface may also require sensor feedback to trigger a stop when contact is established. There is also always a deviation between the nominal design and the produced part, and transferable sensor-based skills can be used to ensure that the desired motion is achieved or a failure is detected. The annotation of assembly tasks directly in CAD software, or encoding them as constraints in the STEP file to be available across different CAD vendors, is intended to bring design and automation closer. The nominal design has a lot of information that can be utilized in motion programming, and information such as material, relative tolerances, and relative transformation between features can be explored in the context of motion programming and other aspects such as part localization and quality inspection.

As with most systems, the choices made in the architecture and control paradigm also have drawbacks. A workpiece-centric motion specification ignores the complexity of aspects of robotics such as singularity avoidance based on where the robot is fastened relative to the workpiece and joint limit and collision avoidance of the robot when executing the motion. The approach of implementing the assembly constraints annotated in the CAD software directly as motion constraints with the reactive exponential controller requires using collision avoidance constraints that may: end up in a local minimum, have different approach motions depending on the initial conditions of the robot or workpiece, or require manual tuning of the constraint gains. The architecture is primarily grounded in the nominal design and nominal behavior of the robot cell. In reality, sensors are affected by noise and calibration, the robot may be in shared human-robot space, the robot cell may have poor absolute positioning precision, and the nominal design may be outdated or have missing information. The architecture also assumes that the workpiece-centric skills are designed to account for deviations between the nominal design and the actual produced parts to be assembled.

For these reasons, there is a lot of potential for further work. Perzylo et al. [17] present a similar assembly programming system for constraint-based specification and control of robot motion. Somani [18] presents a sampling-based path planning approach in the null space of the assembly constraints; this can be used to inform the skills of an ideal approach path and combined with the sensor-based control approach. Simulation of possible robotic assembly sequences based on a design could also help inform the feasibility of a design early on in the design process. Integrating a visualization of a possible control motion when annotating a task in the CAD software could provide useful insight. The controller scheme in eTaSL/eTC that was used is a joint velocity-resolved motion controller, but torque-level closed-loop inverse kinematics schemes exist [19], which would allow for defining more advanced control scenarios and specifying impedance controllers.

Deburring of cast parts

Motivation and problem description

A burr is the excess material that remains attached to the workpiece after a manufacturing process. Deburring is the process of removing these burrs. For sandcast parts, excess material is formed by sprues, runners, risers, and flashing (Figure 11.4). The first three can be removed in a cutting process that leaves a smaller burr to be removed. The flashing is the excess material left in the separation plane between the two molds. Combined, these make up the burrs to be removed in a deburring process.

Deburring can be time-consuming and is considered to be a non-value-added process [21]. The cost of deburring can range from being a small percentage of the total cost to being the largest contributor. If an inappropriate deburring method is chosen, it can eliminate the economic justification for the product [22]. Manual deburring is the most widely used method today. It is a very flexible process, which is convenient if there are small production volumes and variations between each workpiece. During manual deburring, workers are exposed to high noise and vibration levels, and it is a very repetitive task, making it increasingly difficult to find workers willing and able to do the work [23]. It is therefore desirable to automate the deburring process. For high-mix, low-volume production, setup time for a new part and/or workpiece is a critical component of the total cost. Onstein et al. [24] present a literature review on deburring using robot manipulators. The review found that manual deburring is still common for high-mix, low-volume processes

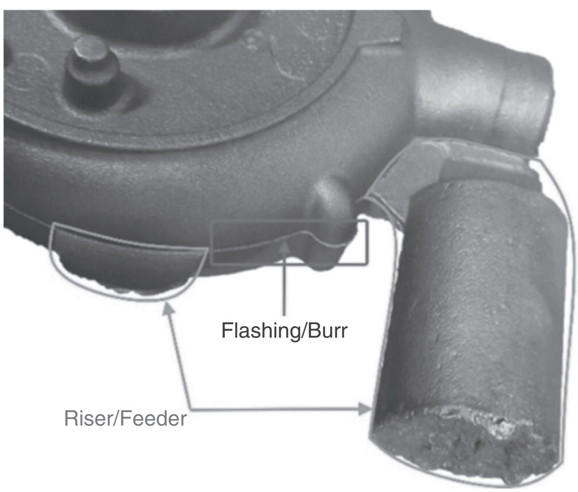


Figure 11.4 Cast part with riser, feeder, and flashing. Copyright obtained from Onstein et al. [20].

because the cost and complexity of automating are too high. To overcome this, there are some challenges that need to be addressed, including, among others, the improved setup/programming method, the process parameter adaptation algorithm, and burr position and dimension estimation for the improved process. These challenges have been the focus of the research in SFI Manufacturing.

The deburring pipeline consists of two main steps: planning and motion execution [24]. Motion execution consists of physical deburring and potential real-time control. This step has not been considered in detail in this research. The planning step consists of path and trajectory planning as well as machining parameter estimation, which will be the focus of the following sections.

Solution

A low setup time requires an automatic and flexible method for generating the tool trajectory for each specific workpiece. A deburring tool trajectory can be generated by demonstrating directly on a reference workpiece with the robot manipulator or by using computer-aided manufacturing (CAM) software and a reference CAD model. Both of these methods are based on a reference model and therefore also assume that the variation between each workpiece is negligible. This assumption does not hold for sand-cast parts, where the geometry between each workpiece varies due to uneven shrinkage and deformations caused by the solidifying process. The uneven shrinkage and deformations can be controlled by optimizing the casting process, but they cannot be completely avoided [25]. As a result, the shape and size of the workpiece vary, as do the size and location of the burrs. These burrs are also larger, on average, compared to burrs formed by other manufacturing processes. These geometric variations mean that a reference model cannot be used to make a tool trajectory alone, and a tool trajectory adapted to each individual workpiece is necessary.

A tool trajectory generation pipeline is proposed in Onstein et al. [20]. A simplified version of this pipeline can be seen in Figure 11.5. To get an accurate representation of each individual workpiece, each workpiece has to be 3D scanned. These 3D scans are then combined into one joint scan through registration. To be able to plan and generate a tool trajectory, some post-processing of the joined scan is necessary. This can either be filtering and further work on the point cloud, or the point cloud can be converted into a 3D mesh through surface reconstruction. The point cloud, or mesh, is then used in a tool for trajectory generation algorithm. In the proposed pipeline, the choice was to use 3D-reconstructed mesh.

Registration and 3D burr detection

Mohammed et al. [26] propose a 3D burr detection method that includes a step for robust registration of 3D scans. The goal of this method is to obtain

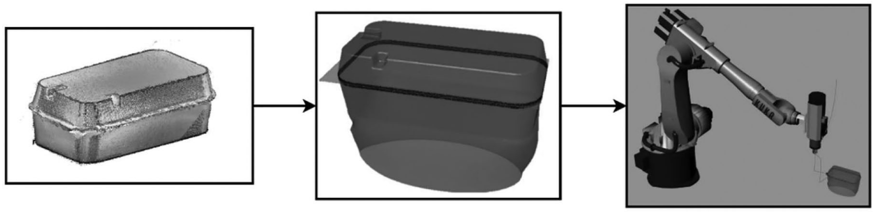


Figure 11.5 Steps from the tool trajectory generation algorithm. The scan is registered to create a joined point cloud. This scan is used to create a 3D mesh representation of the workpiece and the burr region is identified. The generated mesh and the labeled burr region were used to generate the tool trajectory. The figure is inspired from Onstein et al., from which copyright is obtained [20].

more information about the burr position and dimension, which can be used to enhance the deburring process. The obtained information can also be used to develop a process parameter adaptation algorithm.

The proposed method is designed to be robust to missing data in the scans and sensor noise. It uses a novel data-driven approach to learn features that are used to align clean CAD models from a workpiece database with the noisy and incomplete geometry of an RGB-D scan. The learned features improve the registration result using Random Sample Consensus (RANSAC) for CAD to scan registration. For comparison, following Elbaz et al. [27], we compute accuracy, rotation, and translation error averages over scans with burrs and feeders. The accuracy is estimated by taking CAD to scan registration rotation and translation error less than $\theta_r = 10°$ and $T_t = TE < 10$ mm, respectively. The method achieves better accuracy (35%), lower translation error (Δ18.47 mm), and rotation error $\left(\Delta 43°\right)$ compared to traditional approaches using Fast Point Feature Histograms (FPFH) [28].

The method also presents a 3D-vision-based automatic burr detection and height estimation technique. The estimated burr heights are compared with measurements from a high-resolution industrial CT scanning machine and verified. Together with registration, the burr height estimation approach is able to estimate burr height similar to high-resolution CT scans with a Z-statistic value $\left(z = 0.279\right)$. For more information, refer to Mohammed et al. [26].

Tool trajectory generation

Once the workpiece is scanned and registered, as can be seen in the first picture in Figure 11.5, the surface can be reconstructed using a surface reconstruction algorithm like Poisson surface reconstruction [29]. The output of the method can be a triangular mesh that is further used in a tool trajectory generation algorithm. The second image in Figure 11.5 shows the reconstructed mesh.

The tool trajectory generation algorithm is implemented using Grasshopper, which is a programming environment that runs within Rhino 3D (www.rhino3d.com). HAL robotics is integrated into Grasshopper and is used for robot programming.

Input to the tool trajectory generation algorithm is the reconstructed mesh and a labeled burr region. The labeled burr region can be found through 3D burr detection and is used to define the separation plane between the two molds. In Figure 11.5, the labeled burr region is the point cloud contouring the reconstructed mesh, and the calculated separation plane is seen protruding on the sides. First, a tool path is calculated for the specific workpiece. This is done by intersecting the mesh with the separation plane. The next step is to calculate the corresponding tool trajectory. This is done by first choosing a robot to use in HAL robotics. Based on the choice of robot, a tool trajectory is generated. This trajectory can be simulated in the environment and exported as robot-specific code. The last image in Figure 11.5 shows the trajectory simulated in Rhino 3D. For more details about the tool trajectory generation algorithm, see Onstein et al. [20].

Conclusions and recommended further work

For the deburring of high-mix, low-volume productions with geometric variations, there are still challenges that need to be solved to enable automatic deburring. The methods proposed in the sections above are steps toward a more automatic solution.

The 3D burr detection algorithm can estimate the burr location and height based on the 3D scans and CAD model of the part. This information can further be used in a process parameter adaptation algorithm. One example is adjusting the feed rate based on the estimated burr height. This is work that can be addressed in future research.

The tool trajectory generation algorithm generates a trajectory based on a reconstructed mesh that is generated from the 3D scans of each workpiece, as well as a labeled burr region. The generated trajectories have been simulated and tested on a KUKA KR60 robot manipulator. The scanning, registration, and reconstruction of the part have not been addressed in detail in this work. Mohammed et al. [26] present the initial capture setup as well as a deep learning-based registration method where the workpiece is placed on a rotary board and the 3D scanner is in a fixed location. For these scans to be used in a robot setup, they must be transformed into the robot's coordinate system. An alternative approach that is currently being investigated is having the scanner in the hand of the robot. Through hand-eye calibration, the scans come out of the robot's coordinate system ready to use. This can also give a good initial placement of the 3D scans, which reduces the need for post-processing like registration.

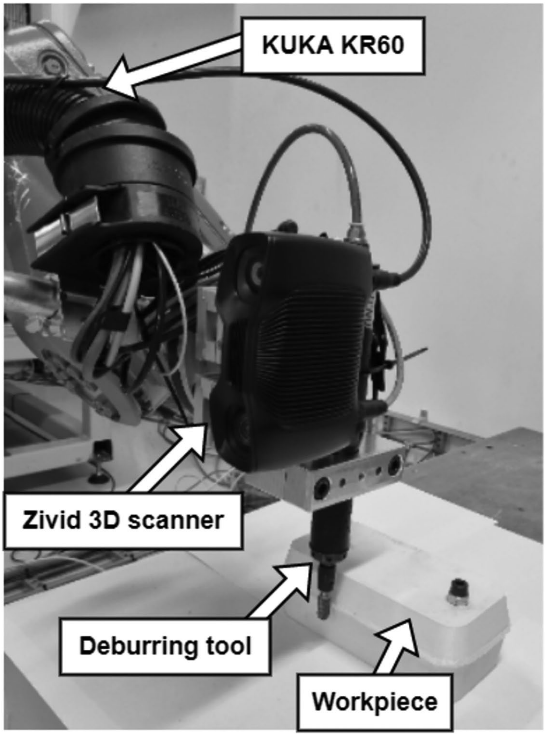


Figure 11.6 Experimental setup for robotic deburring. The setup includes a KUKA KR60 robot manipulator, a Zivid Two 3D scanner, a deburring tool, and the mounted workpiece.

The deburring pipeline consists of two main steps, as mentioned earlier. Until now, the work has mainly been focused on the planning step. To verify the work further, the motion execution step has to be addressed. An experimental setup is being worked on with both the deburring tool and the 3D scanner in the hands of a KUKA KR60 robot manipulator. Figure 11.6 shows an image of the experimental setup. Initial experiments show promising results. More work needs to be done to fully verify the system for automatic robotic deburring.

Automatic loading and unloading of hanging trolleys

Motivation and problem description

Loading and unloading of hangers is a common task in the manufacturing industry. Parts are often transported on trolleys on overhanging conveyors between areas in a factory and inside spray-painting facilities. Manual loading and unloading is labor-intensive and will, therefore, contribute to a large part of the expenses in high-cost countries. Furthermore, the repetitive nature of the tasks can cause muscle strains and other health and safety-related issues and can be considered tedious work. It is, therefore, desirable to take steps toward automating this process.

Solution

Our proposed solution consists of four modules: object tracking, motion prediction, trajectory generation, and trajectory tracking. The modules will be explained in detail in the following.

Object tracking

In order to plan a trajectory for the robot manipulator arm to load and unload objects on the overhead trolley, it is necessary to know where the objects and the hanger are in real time. To this end, a Qualisys motion capture (MOCAP) system was used to track the relevant frames in the environment, as seen in the setup in Figure 11.7a and b.

Specifically, the part frame and hanger frame were tracked in real time, and the robot base frame was initially calibrated as well using the MOCAP system. Five Arqus 12 cameras were used to track the objects at a frequency of 100 Hz. This allows for high-precision marker-based 6-DOF tracking. Additionally, it enables parallel development of motion control algorithms and benchmarking of other object tracking methods. However, it requires markers to be placed on the parts and the hanger in the setup, which is deemed unrealistic in an industrial manufacturing setting.

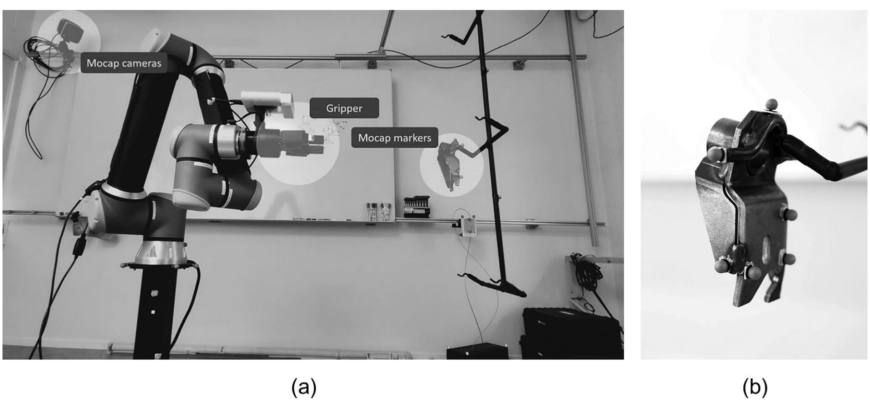


Figure 11.7 (a) Robotic cell setup with robotic arm with gripper, hanger, part, and motion capture cameras. (b) Reflective markers on the part to be manipulated by the robotic arm.

Motion prediction

For this use case, both the parts and the hanger are freely swinging, which must be considered when loading and unloading the hanger. Furthermore, robot arms cannot execute commands instantaneously and therefore introduce an actuation delay, which, given the oscillatory dynamics of the hanger, must be compensated for [30]. A trolley with one part attached is similar to a double pendulum, yet the specific geometry and the constraints at the contact points were seen to cause rather complex behavior. Any analytical model of the system will be difficult to derive, especially when more parts are added to the trolley. Identifying or learning a general model will likely also be challenging, as a multi-part loaded trolley will have many possible configurations.

For small trolley motions and short prediction horizons, it is, however, possible to apply simple methods for predictions. Here, first-order integration of the estimated hanger pose is used. First, the pose measurements are Butterworth low-pass filtered. Then first-order finite differences are used to estimate the 6-DOF velocity $\begin{bmatrix} \boldsymbol{v}_k^\top & \boldsymbol{\omega}_k^\top \end{bmatrix}^\top$:

$$\boldsymbol{v}_k = \frac{1}{\Delta t}\left(\boldsymbol{p}_k - \boldsymbol{p}_{k-1}\right),\ \boldsymbol{\omega}_k = \frac{2}{\Delta t}\mathrm{Ln}\left(\boldsymbol{q}_k \otimes \boldsymbol{q}_{k-1}\right),$$

where $\otimes$ and $\mathrm{Ln}(\cdot)$ denote the quaternion product and logarithmic map [31], respectively. Finally, the same first-order approximation is assumed over the prediction horizon, such that the future pose is estimated to be

$$\boldsymbol{p}_{\text{pred}} = \boldsymbol{p}_k + T_{\text{pred}}\,\boldsymbol{v}_k,\ \boldsymbol{q}_{\text{pred}} = \mathrm{Exp}\left(\frac{T_{\text{pred}}}{2}\boldsymbol{\omega}_k\right) \otimes \boldsymbol{q}_k,$$

where $\mathrm{Exp}(\cdot)$ denotes the exponential map. T_{pred} is the prediction horizon duration, which is comprised of the lags resulting from computation, communication, and actuation.

Trajectory generation

Based on the estimated pose of the hanger and object frames, we plan a pose trajectory for the robot end effector. We propose to blend between a sequential set of time-varying frames to achieve the desired behavior. First, the robot safely approaches the swinging hanger, moves toward the pre-calibrated grasp frame, and grasps, unhooks, and retrieves the object. For the loading sequence, the robot approaches the hanger with the object and loads it back on the hook in a pre-calibrated loading pose in the hanger frame.

Trajectory blending is used to smoothly transition between the different time-varying frames. Linear interpolation is used for the translation, which states:

$$p(t) = p_0(t) + \beta(s(t))\left(p_f(t) - p_0(t)\right),$$

where p_0 and p_f are the initial and final translations, respectively, and $\beta(s):[0,1] \mapsto [0,1]$ is the blending factor. SLERP [32] interpolation is used for the rotation states:

$$q(t) = q_0(t) \otimes \left(q_f(t) \otimes q_0(t)^{-1}\right)^{\beta(s(t))},$$

where q_0 and q_f are the initial and final rotation quaternions, respectively. For the blending factor, a monotonically increasing quintic polynomial with zero initial and final derivatives is used to blend between the frames:

$$\beta(s(t)) = 6s(t)^5 - 15s(t)^4 + 10s(t)^3.$$

For certain parts of a sequential state machine that blends between different transformations, it may be desirable to blend between three or more frames smoothly. For such cases, cubic quaternion spline interpolation was used, with zero initial and final velocity [33].

Trajectory tracking

A Universal Robots (universal-robots.com) UR10e robot manipulator was used with a Robotiq (robotiq.com) 2F-85 gripper to perform the loading and unloading of the trolley.

The desired end effector pose was calculated in real time at a frequency of 100 Hz and passed to the UR10e robot through the RTDE interface using ur_rtde (https://gitlab.com/sdurobotics/ur_rtde). In Figure 11.8, images from the demonstrated loading and unloading task are shown. The trajectory tracking error for the end effector pose is shown in Figures 11.9a and b.

Conclusions and recommended further work

We have shown that the proposed solution is capable of loading and unloading parts to and from different positions on the trolley. The modularity of the setup allows to easily explore and improve different methods. Even when the trolley is oscillating with a large amplitude, the robot can load objects fairly robustly. However, we will in the following point to several important areas of further research related to this application.

First, it is necessary to integrate a machine vision component for the detection and tracking of objects. The current configuration using MOCAP is not

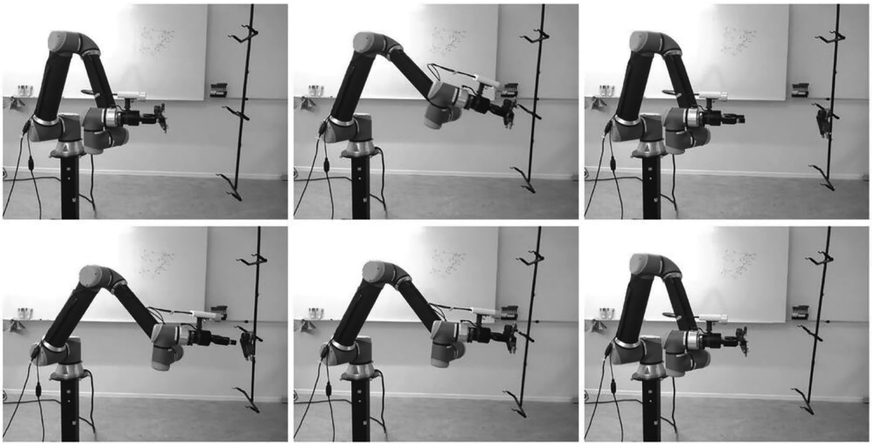
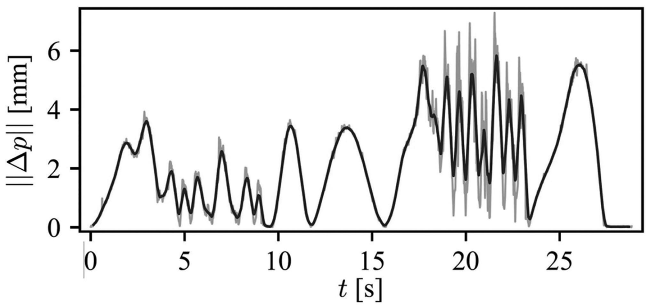
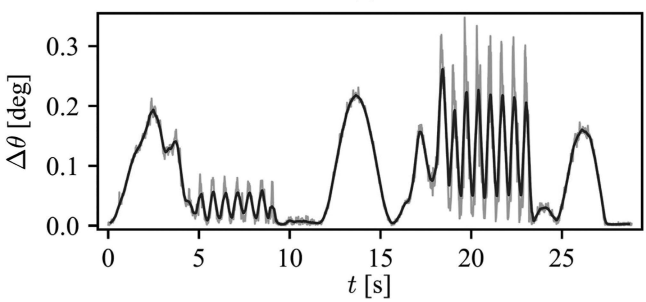


Figure 11.8 Still images from the demonstration of the loading and unloading task.



(a)



(b)

Figure 11.9 Pose tracking error over the duration of the loading and unloading tasks. Both a 31-sample moving average and exact values are shown. (a) The Euclidean norm of the translational error, $\|\Delta p\|$. (b) The absolute angular error, $\Delta\theta$.

considered practical in an industrial setting, as it requires markers on every object to be tracked. For the same reason, a tracking method based on fiducial markers, e.g., ArUco markers, are considered irrelevant for this problem. For future work, we will, therefore, investigate CAD-based detection and tracking methods [34] or other methods based on knowledge of the geometry of the objects. There are, for instance, examples in the literature of a system solely based on 2D computer vision (as opposed to a MOCAP system) that was used to track a trolley in a similar application to ours [35]. However, the parts were not free-hanging on the trolley, and therefore the method did not require multi-object detection and tracking.

We also believe that the mechanical design of the system should be reconsidered for ease of implementing automatic loading and unloading. The slender design of the trolleys is not necessarily optimal for detection and tracking with machine vision. Furthermore, the trolleys are currently free-swinging with low damping, which can lead to lasting oscillations after interactions between the robot and trolley. This can inhibit efficient loading and unloading in an industrial setting, and it is recommended to look into whether introducing mechanical damping could be beneficial.

Bin picking of reflective objects

Motivation and problem description

Bin picking is the task of emptying a box of parts with a robot and is an important building block for flexible and low-volume automation. In automatic bin picking, a sensor system is used to find which part is to be picked by a robotic manipulator arm, in addition to where and how to grasp it. A field of research that has seen considerable effort in recent years is the challenge of picking shiny or reflective parts.

The particular task of picking shiny steel components of various shapes and sizes is an important industrial application. The main challenges from a vision point of view are that these parts are highly reflective, which causes missing 3D information and noisy data. In addition, partially overlapping or adjacent parts must be accounted for, which makes the task of computing possible grasps a difficult tasks [36]. Further challenges include missing 3D information, sensor occlusions, and corner cases; that is, the last components in the bin can be difficult to reach.

Solution

We consider an application where unordered, shiny parts need to be picked from a bin where they lie in a cluttered scene, as illustrated in Figure 11.10a. The goal behind this work is to design a flexible robot set-up that is able to pick parts placed in the bin and deliver them at a specified location.

Robotic set-up

The robotic set-up consists of a UR5 6-DOF robot. A Zivid 3D camera is mounted on the end effector of the robot arm. A camera housing covers the 3D camera to protect it as the robot arm, and consequently, the camera moves to perform picking tasks.

One of the challenges when grasping in a cluttered environment is that grasps become hard to carry out without colliding with the other surrounding parts. For this specific case, the gripper is designed to be slim in order to reach parts that lie in clutter without contact with other parts. In addition, it should be able to pick the last parts from the bin, including the extra challenging case where the cylindrical parts stand upright and perhaps also close to one of the corners in the bin that typically will be picked last (Figure 11.10b). Another challenge when it comes to grasping the specific parts is that they have convex surfaces. This means that the contact surface becomes slightly limited compared to flatter parts. This is addressed by the suction cup on the vacuum gripper, which is compressible and allows the gripper to move a small extra distance to ensure a solid grasp.

With the robotic eye-in-hand setup, it is possible to do 3D imaging from different perspectives (Figure 11.10c) to attain more information than what is possible with a static camera location. This helps prevent sensor occlusions and missing 3D information. The resulting point clouds are seen in Figures 11.10d and 11.10e and illustrate the benefit of imaging from the sides to get more 3D information about the sides of standing cylinders. Getting a good view of the side of the parts is particularly important since our vision solution [36] does not estimate the pose of the individual components but instead attempts to find graspable areas irrespective of their pose. Since the grasp locations are not known *a priori*, the system must in real-time avoid self-collisions, as well as collisions between the robot and the environment, and also differentiate between the part to be grasped and the surrounding parts. The flexibility of our system comes at a cost of increased complexity. To carefully integrate the different modules of the bin picking system, we have designed a state machine for efficient control of the process. It monitors the state of task fulfillment and triggers individual behaviors in the appropriate order.

Grasp pose detection from 3D images

By grasp detection, we mean both recognizing the relevant parts as well as considering how the robot should actually grasp them. 3D data on the parts in the bin are gathered using the Zivid camera mounted on the robot end-effector. Because the parts lie in a cluttered scene, are highly reflective, and have convex surfaces, the 3D point clouds will suffer from noise

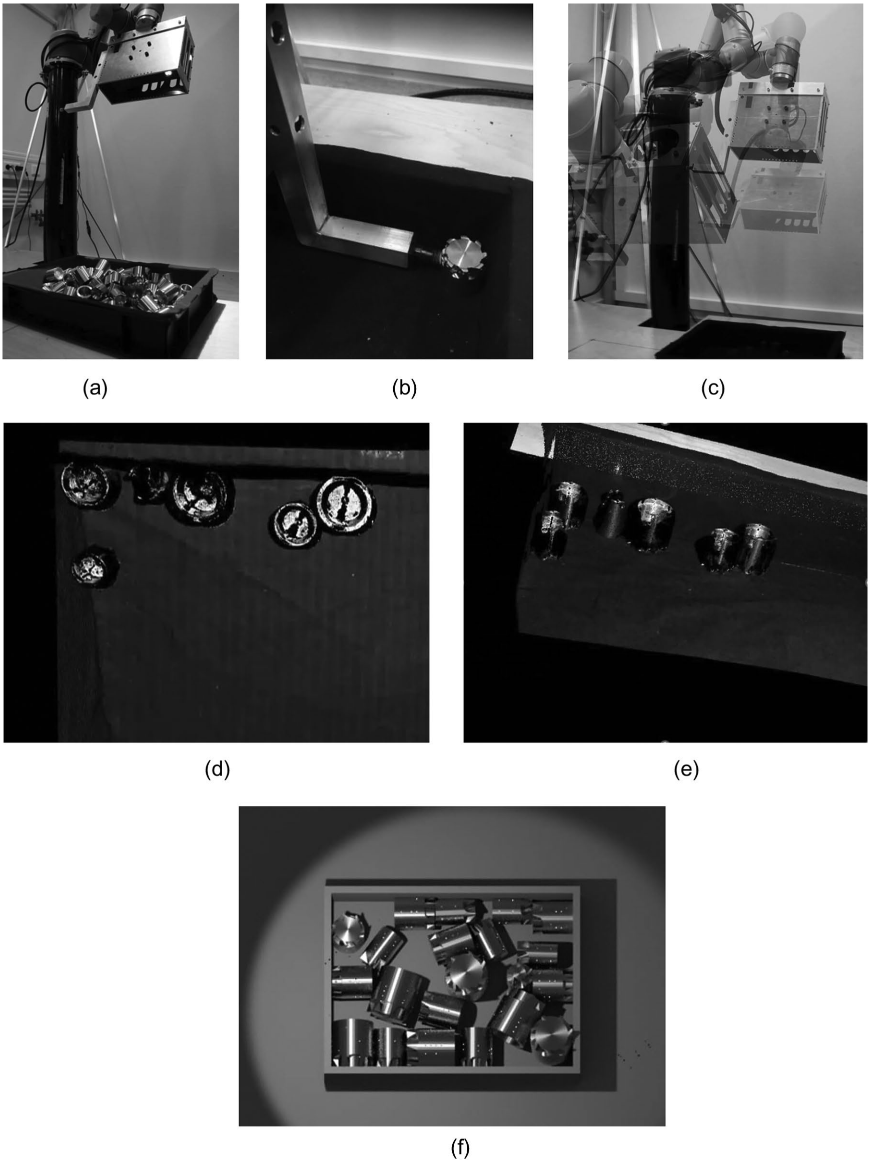


Figure 11.10 (a) The UR5 robot is equipped with a vacuum gripper and a Zivid 3D camera. (b) The setup allows grasping from the side of corner objects. (c) The flexible camera setup makes multiple view angles possible, providing both (d) top view and (e) side view. (f) A simulation framework was used to train grasp poses from 3D images.

and data loss. The sensor is equipped with a projector, which can provide additional noise due to the reflective surfaces. Because of the sparse 3D data caused by reflectivity, a dual-resolution convolutional neural network is used for 5-DOF grasp detection from depth images. It uses a high-resolution focus network to compute the grasp and a low-resolution context network to avoid local collisions. To automatically generate a large data set for training the neural network, a simulation environment was developed (Figure 11.10f), given the known reflectivity and geometric properties of the objects in the bin picking scenario. The deep learning algorithm is explained in more detail in [36]. The possible grasps for the robot are given in camera coordinates, which are transformed to robot coordinates.

Grasp pose selection

The deep learning algorithm outputs several grasps, where each grasp is given as a position and a direction vector only. Although the grasps are ranked, the purpose of the grasp pose selection is to filter out grasps that are obviously wrong or particularly challenging to reach. This could either be because the algorithm wrongly suggested a grasp on the edge of the bin, that the part is not one of the uppermost parts and hence has a high risk of leading to collisions, or that the grasp is kinematically challenging for the robot to execute.

Collision-free path planning

Another crucial aspect of bin picking is to plan paths that the robot can execute without any collisions with the bin or the environment. Especially manipulation in restricted areas calls for motion planning with collision avoidance. If the environment cannot be assumed to be static, changes in the environment can be monitored and fed into the motion planning.

The robot is programmed using Python in a ROS environment, which makes a variety of integrated tools available. One of them is the *MoveIt!* motion planning framework, which integrates directly with the Open Motion Planning Library (OMPL), an open-source motion planning library that implements randomized motion planners.

MoveIt! also offers integration with one or more 3D sensors to enable 3D perception handled by an occupancy map monitor. The occupancy map monitor uses an Octomap to maintain the occupancy map of the environment to survey which voxels in the environment are occupied and which are free to move through. Moveit! was in this case configured with both the Kinect and the Zivid camera, and the respective point clouds are used to build and visualize an Octomap in RViz as the robot moves. Other static obstacles not seen from the Kinect camera were added to the occupancy map [37]. A geometric planner was used, i.e., the planner accounts for the geometric and kinematic constraints of the system. It is based on rapidly exploring random trees (RRT), which typically grow a tree of states connected by valid motions. The optimization objective used was path length minimization.

Conclusions and recommended further work

We have shown that learning from simulations is a viable alternative to collecting large amounts of experimental data; e.g., 6–14 manipulator arms were used over a course of two months to generate more than 800,000 grasps [38]. The drawback is that skills learned in simulation can be difficult to transfer to the real world. Sim-to-real transfer learning is an important research avenue in this respect that should be further investigated. More realistic simulation environments typically give better results. If substantial modeling is required, this can, however, defeat the purpose of learning in the first place.

Another important design choice was the separation into a vision and motion planning module. Although learning servoing of robots is possible, as shown in [38], we chose to explore more traditional methods for motion planning and control. Even if moving the robot between static configurations is well explored, the rather complex gripper design used to enable picking of corner cases leads to a challenging planning problem. More compact sensors will reduce this problem to some extent, but how to maintain manipulability under geometric constraints, as in, e.g. [39], should be further investigated. A possible, simpler, practical alternative to account for the last parts in the bin could be to use a shaking-board to shake the last parts away from the corners. This would also have its own drawbacks, including generating noise.

One of the main challenges of bin picking shiny objects is the noise caused by reflections. Noise reduction is an important ongoing area of research, and it is noticed that this is less of a problem in recent 3D sensors.

Nonlinear model predictive control for robot manipulator trajectory tracking

Motivation and problem description

The rapid adaptation of cost-effective, collaborative, and sensor-guided robot manipulator arms motivates the need for fast and accurate trajectory tracking methods. Especially, one requires methods that can react safely to a dynamically changing environment through sensor information in real-time, for instance, to facilitate human–robot interaction. Optimal control, and specifically nonlinear model predictive control (NMPC), provides a useful framework to achieve these goals. It allows to incorporate the dynamics model as well as other constraints, such as kinematic constraints, singularity avoidance, self-collision avoidance, and obstacle avoidance, explicitly in the planning problem. Furthermore, modern tools for optimization allow the implementation of such methods in real time.

Solution

In the following, an NMPC controller is formulated for the robot manipulator trajectory tracking problem. The performance and real-time feasibility of the approach are demonstrated by grasping a moving object and avoiding a moving obstacle.

Robot manipulator trajectory tracking using NMPC and the SQP real-time iteration scheme

To formulate an optimal control problem (OCP) for the trajectory tracking problem, the model, i.e., the kinematics and dynamics of the robot manipulator, must be defined. The forward kinematics are generally given as $\boldsymbol{h}(\boldsymbol{q}) = \left[\boldsymbol{h}_p(\boldsymbol{q})^\top \ \boldsymbol{h}_q(\boldsymbol{q})^\top\right]^\top$, where $\boldsymbol{h}_p(\boldsymbol{q})$ and $\boldsymbol{h}_q(\boldsymbol{q})$ denote the end effector translation and rotation quaternion, respectively, and $\boldsymbol{q}$ are the joint angles. The equations of motion for the manipulator are generally given on the form

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau}.$$

Defining, $\boldsymbol{x} = \left[\boldsymbol{q}^\top \dot{\boldsymbol{q}}^\top\right]^\top$, one can rewrite this equation on the forward dynamics form $\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x},\boldsymbol{\tau})$ which is then discretized and added as a constraint in the OCP.

For the trajectory tracking problem, the goal is to follow a desired pose trajectory $\boldsymbol{h}^\star(t)^\top = \left[\boldsymbol{h}_p^\star(t)^\top \boldsymbol{h}_q^\star(t)^\top\right]^\top$ while adhering to constraints and secondary goals. To this end the trajectory tracking error is defined as $\boldsymbol{e}(\boldsymbol{q}) = \left[\boldsymbol{e}_p(\boldsymbol{q})^\top \boldsymbol{e}_o(\boldsymbol{q})^\top\right]^\top$, where the translational error is $\boldsymbol{e}_p(\boldsymbol{q}) = \boldsymbol{h}_p^\star(t) - \boldsymbol{h}_p(\boldsymbol{q})$. For the rotational error, the vectorial part of the error quaternion is used:

$$\boldsymbol{e}_o(\boldsymbol{q}) = \eta^\star(t)\boldsymbol{\varepsilon}(\boldsymbol{q}) - \eta(\boldsymbol{q})\boldsymbol{\varepsilon}^\star(t) - \left[\boldsymbol{\varepsilon}^\star(t)\right]_\times \boldsymbol{\varepsilon}(\boldsymbol{q}).$$

Here η and $\boldsymbol{\varepsilon}$ denote the scalar and vectorial parts of the rotation quaternions, respectively, and $[\cdot]_\times$ is the skew-symmetric matrix operator. Defining a cost function from the trajectory tracking error over a horizon of N steps, and regularizing the joint accelerations and joint torques to generate smooth and energy-efficient motions, we get the following OCP:

$$
\begin{aligned}
\min_{\boldsymbol{x},\tau} \quad & \sum_{i=0}^{N-1}\left(\left\|\boldsymbol{e}(\boldsymbol{x}_i)\right\|_{\boldsymbol{Q}}^2 + \left\|\ddot{q}_i\right\|_{\boldsymbol{R}_a}^2 + \left\|\tau_i\right\|_{\boldsymbol{R}_\tau}^2\right) + \left\|\boldsymbol{e}(\boldsymbol{x}_N)\right\|_{\boldsymbol{S}}^2 \\
\text{s.t.} \quad & \boldsymbol{x}_{i+1} = \boldsymbol{f}(\boldsymbol{x}_i, \tau_i),\ i = 0,\ldots,N-1 \\
& \boldsymbol{x}_{\min} \le \boldsymbol{x}_i \le \boldsymbol{x}_{\max},\ i = 0,\ldots,N, \\
& \tau_{\min} \le \tau_i \le \tau_{\max},\ i = 0,\ldots,N-1 \\
& \ddot{q}_{\min} \le \ddot{q}_i \le \ddot{q}_{\max},\ i = 0,\ldots,N-1, \\
& \boldsymbol{x}_0 = \bar{\boldsymbol{x}}_0,
\end{aligned}
$$

where the latter constraints define the bounds on the optimization variables, including the initial condition from the sampled state $\bar{\boldsymbol{x}}_0$. $\|\cdot\|_{\boldsymbol{A}}^2$ denotes the squared Euclidean norm weighted by the matrix $\boldsymbol{A} > 0$.

The above nonlinear OCP is solved in a receding horizon fashion as a NMPC problem. The problem is solved using the sequential quadratic programming (SQP) method with the Gauss-Newton Hessian approximation, and it is warm-started using the real-time iteration (RTI) scheme [40]. The RTI scheme warm-starts the solver by shifting the previous solution by one time step and then does a single iteration of the SQP algorithm. Moreover, the RTI scheme splits the SQP iteration into two phases: the preparation phase and the feedback phase. The preparation phase is independent of the initial state and can thus be done before sampling the system state, thus significantly reducing the feedback delay, as illustrated in Figure 11.11.

The kinematics and dynamics expressions are calculated with urdf2casadi [41], given a URDF model file for the robot. The resulting NMPC problem is solved using the SQP RTI solver in acados [42] with the HPIPM [43] interior point QP solver.

The ability of the trajectory tracking controller to react to a time-varying environment was first demonstrated by grasping a moving object. An optical

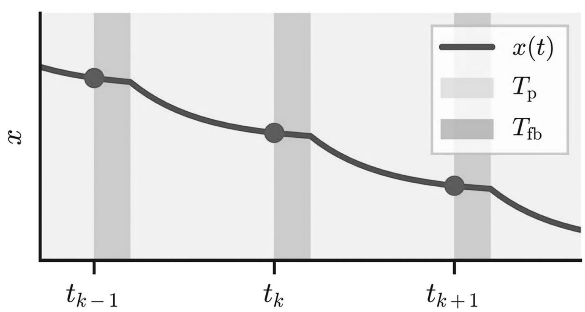
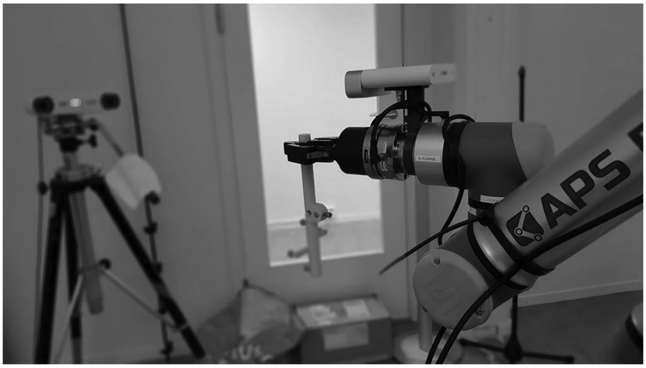
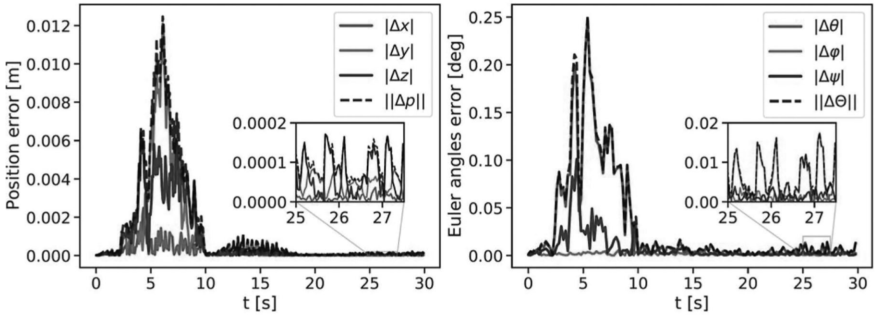


Figure 11.11 RTI loop with T_p and T_{fb} denoting the preparation phase and feedback phase, respectively. The points indicate the state sampling times.

pointer (tracked by a Polaris Vicra optical tracker system) was moved around while a UR10e robot planned a path toward it and grasped it using a Robotiq 2F-85 gripper, seen in Figure 11.12a. The desired trajectory was determined by interpolating between the initial pose and the moving target pose while following a third-order exponential blending profile [44]. Since the UR10e robot does not provide a direct torque interface, the joint velocities from the solver were passed to the velocity interface using ur_rtde (gitlab.com/sdurobotics/ur_rtde). The NMPC problem was solved over a time horizon of 0.6 s, with time steps of 40 ms. The limiting factor for the chosen step size was the frame rate of the tracking system, as the mean computation time for the solver was only 8.14 ms. The trajectory tracking errors can be seen in Figure 11.12b.



(a)



(b)

Figure 11.12 (a) UR10e robot manipulator grasping pointer tracked by optical tracker. (b) Trajectory tracking error during demonstration of grasping moving object, represented as magnitude translational error and magnitude of *xyz* Euler angles error.

Incorporating collision avoidance

The NMPC approach to solving the trajectory tracking problem can also be extended to consider collision avoidance. By adding additional constraints and cost terms, we can plan the robot's motion to avoid self-collisions and dynamic obstacles. The robot links are approximated by a set of spheres, as illustrated in Figure 11.13. Similarly, obstacles are approximated as a second set of spheres. The trajectory tracking OCP can then be extended to include obstacle avoidance by adding constraints on the minimum distance between the link set and the obstacle set [45]. Analogously, constraints can be added to ensure no self-collision. Furthermore, an additional cost is included to favor a safe distance to the obstacles when possible. For every pair of obstacle spheres and link spheres, we define the cost, $C(q) = Q_O F(q)^2 G(q)^2$ where Q_O is a weighting parameter and

$$G(q) = \frac{\beta^2 - \delta^2}{d(q)^2 - \delta^2} - 1$$

is the repulsive potential of the obstacle. Here $d(q)$ is the distance between the sphere centers, δ is the minimum allowed distance, and β is an activation threshold. The cost is forced to stay zero outside the activation threshold by the logistic function $F(q)$. Thus, the cost starts at zero at the activation threshold β and increases as we approach the minimum distance δ.

Dynamic obstacle avoidance was demonstrated by having the UR10e robot track a trefoil knot trajectory while moving the pointer toward the robot to disrupt its nominal motion. This was done by incorporating the position of the pointer in the optimization problem through the cost $C(q)$. In Figure 11.14a and b, it is seen how the robot deviates from the desired trajectory to avoid the approaching obstacle. Adding collision avoidance in this case increases the mean solver time to 9.43 ms.

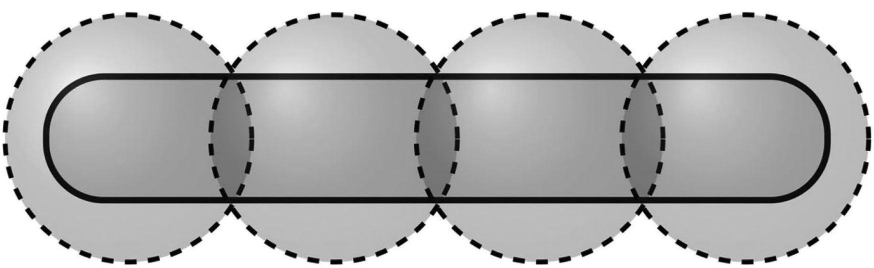
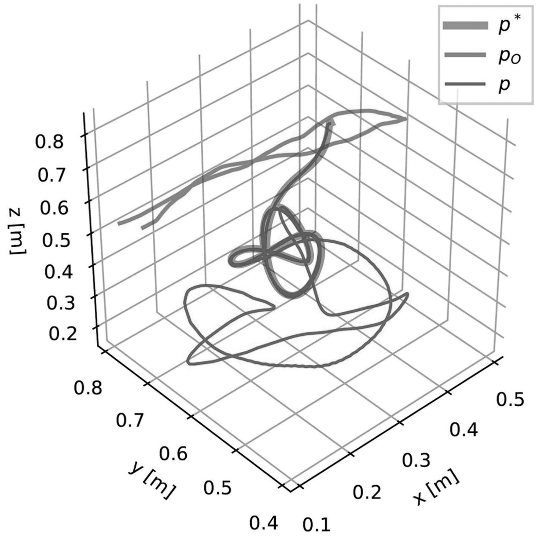
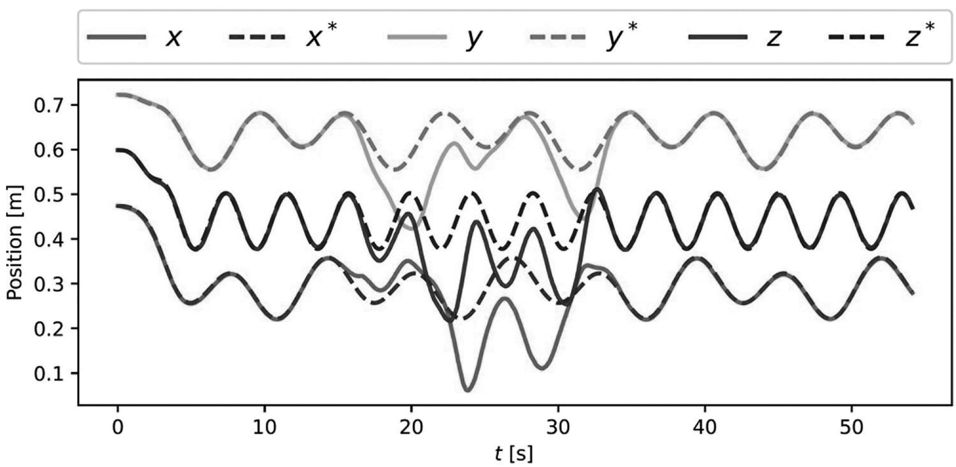


Figure 11.13 Exemplary approximation of a robot link as a set of spheres.



(a)



(b)

Figure 11.14 (a) As the moving obstacle with position p_O approaches the robot, the end effector position p deviates from the desired position $p\star$ to avoid the obstacle. (b) Desired and actual *xyz* position of the robot end effector.

Conclusions and recommended further work

With modern optimization tools and hardware, it is possible to solve the trajectory tracking optimization problem with nonlinear robot dynamics in a receding-horizon fashion in real-time. This opens up possibilities in terms of performing more agile and energy-efficient operations. Furthermore, the NMPC framework provides a convenient way of considering a dynamic environment in the motion planner. This was demonstrated with a UR10e robot manipulator grasping and avoiding moving objects. The proposed NMPC approach could also be applied in a human–robot interaction context. By using an appropriate sensor system and human pose estimation methods [8], one can incorporate the predictions as objects in the optimization problem to avoid or interact with in real-time. The trajectory tracking NMPC can also be extended to more complex systems like mobile manipulators or floating base manipulators [46], given a model of the system dynamics.

For further work, the predictive nature of NMPC allows the incorporation of predictions from estimation methods over the planning horizon to more intelligently navigate the environment. Moreover, including system identification and dynamics learning approaches to improve the dynamic model is useful, possibly jointly with the estimation system in a stochastic NMPC setting.

Task-priority set-based reactive control

Motivation and problem description

Industrial robots are often serially linked, revolute-jointed manipulators with at least six DOF. This kinematic structure allows for a large volume around the robot where the robot's end-effector can be placed at any position or orientation relative to the base frame of the robot. In practice, many tasks that robots are to perform are defined by fewer DOF. An example of this is spray painting, where a circular nozzle can be rotated around the vector going out of the nozzle with no change in the area covered during spraying. The additional DOF of the robot with respect to the task can be exploited to achieve secondary tasks, such as maintaining an elbow-up configuration, and creates a form of prioritization of different tasks that are to be achieved simultaneously.

One of the earliest examples of realizing a task in the null space of a higher priority task is the work of Liégeois [47] from 1977, where a robot arm was to move a pencil along a circle with a lower priority task that attempted to maximize the distance to the joint limits. A study by Hanafusa et al. [48], from 1981, is another early example where the main task was avoiding collision with a pillar while the secondary task was to move the manipulator from one configuration to another. As mentioned in Section 'Reactive control for assembly', Samson et al. [15] describe the task-function approach in depth and investigate when a task is realizable on a robotic system. In [49] Siciliano and Slotine demonstrated placing multiple tasks in a prioritized stack by projecting each lower-priority task in the null space of the higher-priority tasks. In many of the early works, task-controllers were defined such that some expression would converge to zero, and the lower priority task would be a controller that represents the descent gradient of some other optimization.

In practice, we may desire for robots to both ensure some expression converges to zero, that some expression is generally minimized, and that an expression does not exit some set. Suppose, for example, we have

$$h_1(q) = \left\| \left(d_1(q) \times d_2 \right) \right\|^2,$$

where $q \in \mathbb{R}^{n_q}$ are the robot joint variables, $d_1(q)$ is a direction vector from the robot defined in world coordinates and d_2 is a direction vector in the world coordinates,

$$h_2(q) = \sum_{i=1}^{n_q} \left(\frac{q_i - 0.5 q_{i,\max} + 0.5 q_{i,\min}}{q_{i,\max} - q_{i,\min}} \right)^2,$$

where $q = \left[q_i, \ldots, q_{n_q} \right]^T$, $q_i \in \left[q_{i,\min}, q_{i,\max} \right]$ owing to the joint limits of joint, i and

$$h_3(q) = \| p(t) - p(q) \|^2,$$

where $p(q) \in \mathbb{R}^3$ describes the position of the tool and $p(t) \in \mathbb{R}^3$ describes the desired trajectory to track. This could describe, for example, a trajectory that the tip of the pen should draw in the task h_3, that distance to joint limits should be maximized in h_2, and that we should be pointing in the general direction of the drawing surface in h_1. As the pen does not need to be exactly perpendicular to the drawing surface, h_1 does not need to converge to a set, but to either remain in a set if it started there or converge to the set if it did not start there.

Combining expressions made to converge to zero, minimization of expressions, and set-constraining tasks have been achieved by frameworks such as the work by Moe et al. [50], Aertbeliën and De Schutter [14], Mansard et al. [51], and many others. In SFI Manufacturing, the task-priority approach employed by Moe et al. [50] was used to investigate task-priority approaches for industrial applications.

Solution

Two industrial applications were investigated: spray-painting and wire-arc additive manufacturing. The examples were chosen as they are tasks where the overall objectives, i.e., to cover a surface in paint and weld along a path, have underlying set-based tasks involved, and are redundant with respect to six DOF robot arms.

Spray painting

The objective of the spray painting application is to coat a surface with spray paint using a robotic manipulator with a nozzle fixed at its end-effector. This is achieved by implementing two tasks [52]: a spray task and a field-of-view task. Figure 11.15 illustrates the variables involved in the tasks. The vector $\boldsymbol{a}(q)$ points in the direction of the spray nozzle, $\boldsymbol{p}_e(q)$ is the position of the spray nozzle on the robot, $z = h(x, y)$ describes the surface to be sprayed in terms of world coordinates x and y, $\boldsymbol{p}_i$ is the point of intersection between the surface and the line l formed by $\underline{a}(q)$ and $\boldsymbol{p}_e$, resulting in a distance between the nozzle and the surface of $\bar{k}$, and $\boldsymbol{N}$ is the normal vector of the surface at point $\boldsymbol{p}_i$.

The spray task ensures that, as a spray pattern is defined on a surface, the distance $\bar{k}$ between the nozzle and the point of intersection should remain constant and that the point of intersection follows a parameterized spray pattern on the surface. The field-of-view task ensures that the angle between

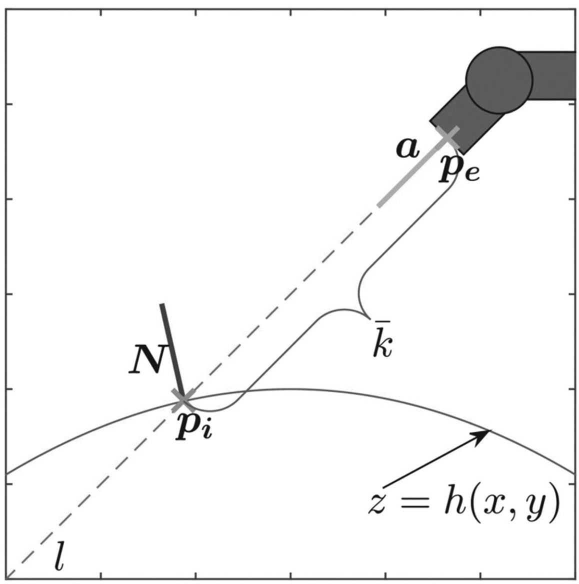


Figure 11.15 Illustration of a spray-painting tool of the robot, pointing along the vector *a* toward the surface *z* at point p_i. Copyright was obtained from Moe et al. [52].

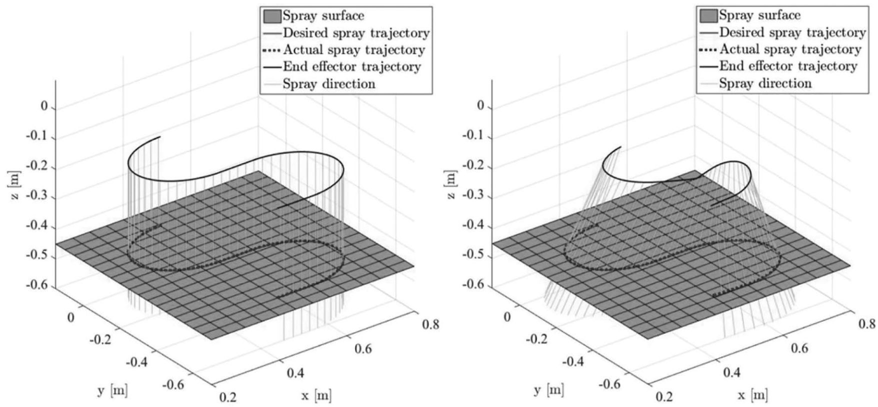


Figure 11.16 Comparison of the resulting trajectory of the nozzle with respect to the surface. Left: Nozzle orientation with respect to the surface normal is fixed. Right: The angle formed by the nozzle and the surface normal is allowed to vary from 0° to 20°. Copyright was obtained from Moe et al. [52].

$\boldsymbol{a}$ and $\boldsymbol{N}$ does not exceed a maximum permissible angle. For further details and derivations of the task, see [52].

Compared to fully defining the trajectory to be executed, the task-priority approach defined by Moe et al. allows for deviation in the angle of the nozzle with respect to the surface normal. This is illustrated in Figure 11.16. By using the field-of-view task, the controller can achieve the objective with less overall movement of the whole arm, and subsequent experiments using a UR5 show that the resulting motion is potentially more energy and time-efficient.

Wire-arc additive manufacturing

In the wire-arc additive manufacturing application [53], the objective was to create a cylinder using a MIG and cold-metal transfer welding gun attached at the end-effector of the manipulator. The cylinder was defined as a helical path, and two approaches were compared: a fixed orientation with respect to the surface approach and a task-priority approach. The task-priority approach used a positioning task such that the tool center point follows the helical path and a field-of-view task allowing for deviation in the angle between the surface normal and the welding gun of up to 6°. Figure 11.17 shows the resulting structures. The left image shows a cylinder created using a fixed orientation with respect to the welding surface normal, and the right image shows a cylinder created using the field-of-view task.

In the field-of-view approach, the orientation of the welding tool varied between 0° and 6° with respect to the welding surface, with the highest angle occurring at the point on the helix farthest from the base of the robot.

Figure 11.17 Comparison of cylinders created using fixed orientation, left image, and using the field-of-view task, right image. The images appeared in Evjemo et al. [53], an open-access article under the CC BY-NC-ND license. We thank the authors for accepting the re-use in this chapter.

The overall result was a structure that had a buildup of material in certain areas, and more volumetric deformation from the desired structure.

Conclusions and recommended further work

In the applications investigated in SFI Manufacturing, the task-priority approach worked well for robotized spray painting, but there are unsolved research questions in connection with additive manufacturing. In spray painting, the freedom afforded by a more advanced control strategy allowed the system to find a motion that achieves the objectives in a more energy- and time-efficient manner. In wire-arc additive manufacturing, the freedom of variable orientation of the welding gun offers potential advantages in control of the robot but introduces structural errors, as wobbling in the walls and varying material deposit. These unwanted effects may be a result of the underlying process, namely MIG welding with cold-metal transfer, being sensitive to reorientation and movement with respect to the welding pool. The differing results from the two applications illustrate that task-priority approaches allow for new optimization opportunities, but that the tasks used must be well grounded in constraints affecting the underlying process and overall objective.

Conclusions

Sensor developments have benefited from the rapid progress in consumer electronics, and as a result, sensors have steadily become cheaper, more compact, user-friendly, and provide better sensing quality. They are now an integral part of many manufacturing processes and have enabled the use of industrial manipulator arms in a range of new areas. Increased computational capacities have also paved the way for new algorithms within machine vision, such as deep learning. These typically rely on a large amount of training data as well as computational capacity to train and use these algorithms. These developments have become essential for flexible automation, as they can prevent some of the costly and time-consuming adaptations necessary in small-batch productions.

In this chapter, we have investigated four applications of sensor-guided motions: reactive control for assembly, deburring of cast parts, automatic loading and unloading of hanging trolleys, and bin picking of reflective objects. To fully benefit from the possibilities of increased use of sensors, new control methods are often necessary. Here, we have also investigated trajectory tracking using NMPC and set-based task-priority, for reactive control. For each of the topics, we have described our solution and provided recommendations for further research.

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Chapter 12

Welding of dissimilar metals

A comparative study

Siri Marthe Arbo, Ivan Bunaziv, Xiaobo Ren, and Sverre Gulbrandsen-Dahl

Introduction

Sustainable, lightweight and high-performance products are of undeniable importance toward a low-emission society based on a circular economy. New multi-material products (MMPs) are regarded as a global trend with respect to product design and optimal choice of materials. Moreover, MMPs can increase the performance and functionality of components [1]. However, a broader application of the promising multi-material solutions is still hindered by restrictions in design flexibility, challenging of joining, high risks of interfacial cracking and a lack of predictability of properties. The sustainable development of MMPs requires the ability to optimize material choice, material processing, interface properties and product performance simultaneously.

Welding is a key joining technology for the production of MMPs of dissimilar metallic components. The ability to join dissimilar metals will open new doors with regard to product design and manufacturing, as well as enable the replacement of parts of a component with lightweight materials through joining. How to establish the process-microstructure-property-performance relationship for the selected welding technologies for developing high-performance MMPs is a key challenge for the industry.

In SFI Manufacturing, there are several industrial cases related to the joining of dissimilar metals, e.g., the joining of dissimilar aluminum alloys, aluminum to steel, hard material to aluminum or steel and copper to aluminum, among others. In this chapter, we aim to compare different welding technologies in five different categories: (1) design flexibility, (2) productivity, (3) quality, (4) intermetallic compound (IMC) formation and mitigation strategies and (5) technology accessibility and maturity. The categories are regarded as essential when selecting a welding technology and evaluating its feasibility and suitability for multi-material joining. The welding technologies that are studied in SFI Manufacturing and are compared in this chapter include both solid-state welding methods, i.e., roll bonding, friction stir welding (FSW), hybrid metal extrusion & bonding (HYB) and fusion welding methods, i.e., cold metal transfer (CMT) welding, laser beam welding

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(LBW) and laser-assisted arc welding (LAAW). The authors have not seen any published literature comparing these methods regarding MMP welding.

As is known, understanding and controlling the formation of IMC layers is the key to achieving high-quality welds of dissimilar metals, which is described in Section "IMC – characterization and mitigation strategies". The basic principles of the selected welding methods are described in Section "Basic introduction to the evaluated welding technologies". Section "Comparison framework" describes the comparison of different welding methods. In Section "Sustainability and circularity of multi-material products", the importance of sustainability and circularity in the design of MMPs is highlighted. The summary of this chapter and the perspective of future research are addressed in Section "Summary and perspective".

IMC – characterization and mitigation strategies

One of the main challenges related to the welding of dissimilar metals is the formation and growth of hard and brittle IMCs along the joint interface, which strongly influence joint quality and performance. It is important to obtain a better understanding of the underlying mechanisms of the formation of IMC, including the influence of alloying elements on the IMC formation.

The IMCs form due to limited solubility between the metals to be joined, which can be seen from the binary phase diagrams of the respective metal systems. For most dissimilar metal systems, i.e., iron-aluminum, aluminum-copper, titanium-steel or aluminum-nickel, the IMC phases have been classified as brittle, and excessive formation of these phases is harmful to the mechanical properties of the joint. The optimal thickness of the IMC layer will depend on the properties of the phases and the IMC layer morphology. However, in the scientific literature, a critical layer thickness of 10 μm that should not be exceeded has been proposed [2]. Thus, the metallurgical suitability of the base materials to be joined is important to evaluate prior to joining [3]. In addition to metallurgical suitability between the base materials, the formation and growth of the IMC are also strongly influenced by the temperatures reached during welding. An illustration of an IMC formed in a dissimilar metal joint during fusion welding is shown in Figure 12.1.

Influence of alloy selection of base materials or filler wire

There exist numerous dissimilar metal alloys, all with unique properties depending on their combination of alloying elements. These alloying elements will also play a significant role in IMC formation and growth. Advanced characterization [4] and multi-scale modeling (based on atomistic modeling by density functional theory) [5] have been developed in SFI Manufacturing in an attempt to better understand the IMC formation related to the chemical composition of the base materials and their individual mechanical

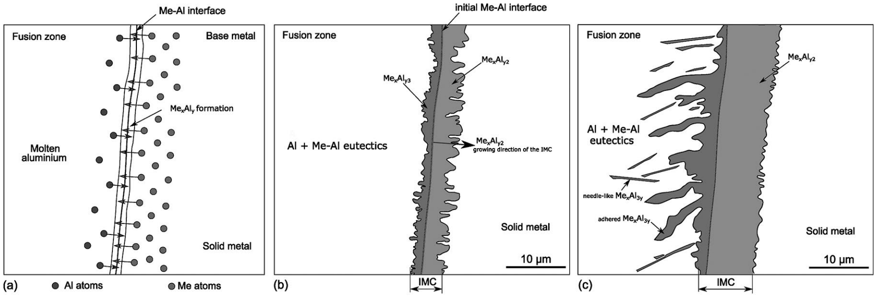

Figure 12.1 IMC layer formation illustrated for metal (Me)-aluminum (Al) system is high melting point metal, i.e., steel, titanium or copper, at (a) activation stage due to high temperatures, (b) and (c) formation and growth of Me_xAl_y phases. Note that in solid-state welding, like FSW and HYB, where no melting occurs, the IMC formation and growth kinetics will be different from those outlined in the figure.

properties. The main emphasis has been on documenting the influence of selected alloying elements found in steel and aluminum alloys to optimize steel-aluminum joints [6]. From this work, it was found that silicon and manganese in aluminum and chromium and nickel in steel reduce IMC formation and growth. Thus, optimizing the base material selection can strongly contribute to reducing IMC formation and growth. However, it may also limit the possible strength of the component. For welding methods that need filler wire addition, adjusting the filler wire chemistry could be a desirable strategy. The change in IMC formation and growth rate as a result of alloying elements is due to (1) their ability to restrict or promote the diffusion of atoms across the joint interface; (2) their participation in the phase formation along the interface, thus, other less brittle phases can be promoted to form along the interface, resulting in higher joint strength and performance; and (3) them being present in solid solution within the formed phases through atomic substitution, thus affecting the growth rate.

Different characterization techniques can be utilized to characterize the IMCs that form along the joint interface for selected material combinations and for different welding methods. Key information regarding the chemical composition, compound crystal structure and atomic position of elements within the crystal structure was used to perform calculations based on first principles to estimate the elastic properties of the identified IMCs [7]. The calculated elastic properties of the IMCs largely agreed with the performed nanoindentation measurements. The methodology shows that a multi-scale modeling approach, coupled with advanced characterization, can play an important role in the design and manufacturing of MMPs while minimizing the detrimental impact of the IMCs. More research is encouraged for desirable dissimilar metal combinations to explore the main influential alloying elements and possible alloying strategies for reduced IMC layer formation and growth.

Mitigation by the introduction of metallic interlayers

Another explored mitigation strategy is to place a metal interlayer between the two base metals at the interface to be joined. This possibility was explored within SFI Manufacturing. The interlayer functions as a barrier, restricting contact between the base metals and thus the formation of the unwanted IMC. The new interlayer may either result in no IMC formation or result in the formation of new IMC layers with one or both base materials, depending on the metallurgical compatibilities. Preferentially, these new phases should have more desirable mechanical properties. Typical interlayer metals used in dissimilar metal joints include nickel, silver, copper and cobalt. The effect of using interlayer has been demonstrated for different dissimilar metal combinations [8–11].

Three criteria are important when selecting an interlayer material: (1) metallurgical compatibility between the interlayer and base metals, seeking metal interlayers with high solubility of both. If IMCs are formed, evaluating the mechanical properties of these IMCs compared to the original will determine the interlayer potential (2) and the thickness of the interlayer. The thickness of the interlayer will both depend on the joining technique applied and the growth rate of potential IMC that might form, as well as (3) mechanical properties to ensure that the interlayer itself does not become the weakest part of the joint. Melting temperature is also an important physical property to consider when choosing the interlayer related to the welding technique to be utilized.

Basic introduction to the evaluated welding technologies

There exist several different solid-solid, solid-liquid and liquid-liquid welding technologies that can be used for the production of MMPs. For many years, fusion welding methods were the dominant techniques used for joining. The great advantage of solid-state joining is the ability for material coalescence at temperatures essentially below the melting point of the base materials to be joined. Since there is no melting involved, the metals being joined will largely retain their microstructural integrity without forming a fusion zone and a wide heat-affected zone (HAZ) with degraded properties, which is the main problem with traditional fusion welding. For multi-material joining, solid-state welding methods offer considerable advantages compared to fusion welding due to the reduced risk of excessive IMC growth and subsequent interfacial cracking. Thus, the selection of welding technology determines the functionality and possible product application. In this chapter, selected

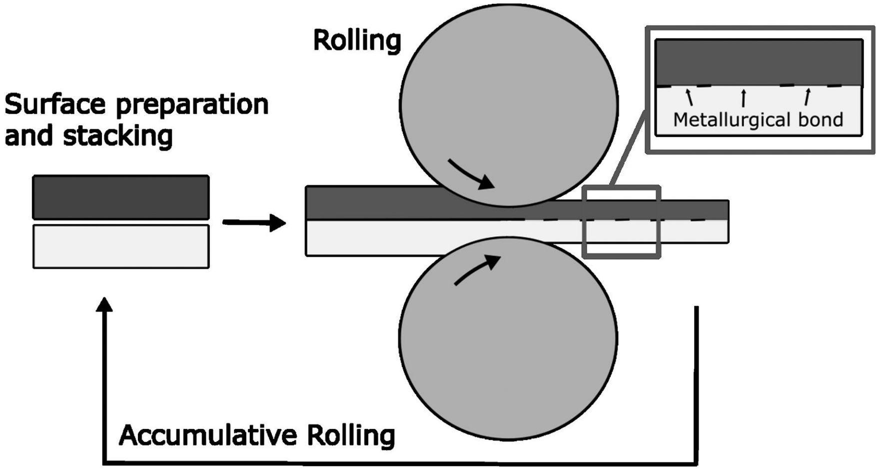

Figure 12.2 Schematic illustration of rolling bonding.

welding technologies that have been studied within SFI Manufacturing are evaluated and compared to determine their limitations and suitability for the welding of MMPs. Only a limited comparison of the selected technologies for welding of dissimilar metals has been previously published.

Cold Pressure Welding by rolling

As stated by Bay [12], materials that cannot be welded together by traditional fusion welding often respond well to joining by solid-state welding techniques known as cold pressure welding. This can be achieved, for instance, by rolling, then referred to as roll bonding. In roll bonding, two plates are stacked together after surface preparation and sent through a rolling mill, achieving sufficient plastic deformation due to surface expansion to form a bond between the deformed sheets [13]. The steps are illustrated in Figure 12.2. Thus, the technique combines joining with metal forming of the base materials.

The roll bonding process can be either performed cold, warm or hot, depending on the applied process temperature and materials to be joined. Roll bonding involves one single pass through the rolling mill, while to produce highly deformed, ultra-fine layered composite materials, accumulative roll bonding can be performed. Hence, pre-rolled material composites are stacked and subjected to rolling numerous times. For all process variations, pre- or post-heat treatment can be applied to achieve the desired microstructure and mechanical properties.

The achieved bond strength is strongly influenced by the actual surface expansion, cleanliness, preparation of the surface to be joined and the temperature at which the process is performed [14]. During surface preparation, a work-hardened surface layer is formed at the same time as contaminations present on the surface are removed. During joining, this surface layer fractures due to the expansion of the surface. Because of the high normal pressure applied, fresh metal is extruded through these surface cracks, and metallurgical bonds are established where the fresh metal from the opposing surfaces meet. A minimum surface expansion is needed, often referred to as the threshold deformation, to achieve a bonding. This depends on the materials to be joined [12].

Friction Stir Welding (FSW)

FSW is a popular solid-state joining technology developed at TWI Ltd in 1991 [15]. In the FSW process, two plates are placed adjacent to each other and firmly pressed together. A specially designed tool, consisting of a shoulder with a rotating pin in the center, is used to achieve bonding between the plates. Prior to the welding operation, the pin is plunged into the plates along the adjoining edges until the shoulder touches the top of the base materials. During welding, the tool moves along the interface of the plates, and a joint is formed as a result of plastic deformation and heat generated by the friction and high rotation speed of the tool. The process is illustrated in Figure 12.3. The process is strongly influenced by several process parameters, such as normal force, rotational speed, welding speed, tool position and tool design. The process parameters must be optimized to avoid the formation of welding defects. Generally speaking, FSW has proved useful in producing high-quality joints between a large range of dissimilar metals [16].

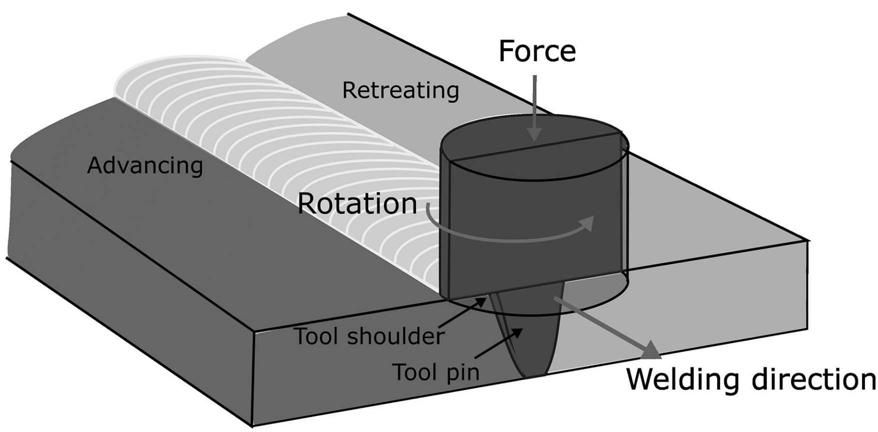

Figure 12.3 The principle of the FSW technique.

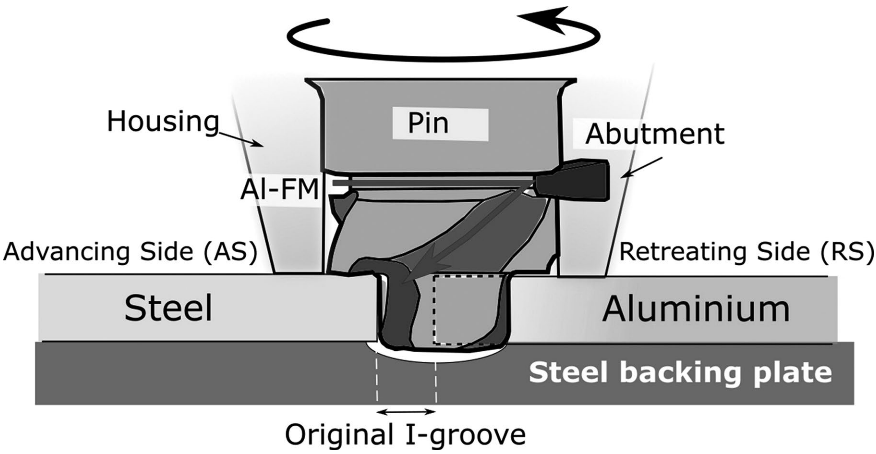

Figure 12.4 Illustration of a possible experimental set-up during aluminum-steel butt welding using the HYB PinPoint extruder [18].

Hybrid Metal Extrusion & Bonding (HYB)

The HYB process has been developed by HyBond, which is a solid-state joining method for metals that utilize continuous extrusion as a technique to squeeze the filler material between the two materials to be joined under high pressure to achieve metallic bonding. The principle of the HYB process is illustrated in Figure 12.4. The HYB technology was originally developed for welding of aluminum alloys, and it has been further developed for welding of dissimilar metals, e.g., aluminum-steel, aluminum-titanium and aluminum-copper, among others [17]. One of the great advantages of the HYB process compared to conventional solid-state joining methods like FSW is that the HYB process involves the use of filler metal additions, which enables flexibility in the design and manufacturing of MMP.

Cold Metal Transfer (CMT) welding

CMT welding was developed by Fronius of Austria in 2004. It is a modified Metal Inert Gas (MIG) welding method based on a short-circuiting transfer process [19] (Figure 12.5). The CMT welding process is characterized by its extremely low heat input and stable arc, which makes it a suitable joining method for dissimilar metals, e.g., aluminum-steel joints.

The CMT welding process significantly reduces the heat input compared to other MIG/MAG processes through digital process control that automatically detects short circuits and then helps to detach the droplet by retracting the wire. The arcing phase is very short in CMT welding. Therefore, the heat input is reduced, which is preferable for welding dissimilar metals. The CMT

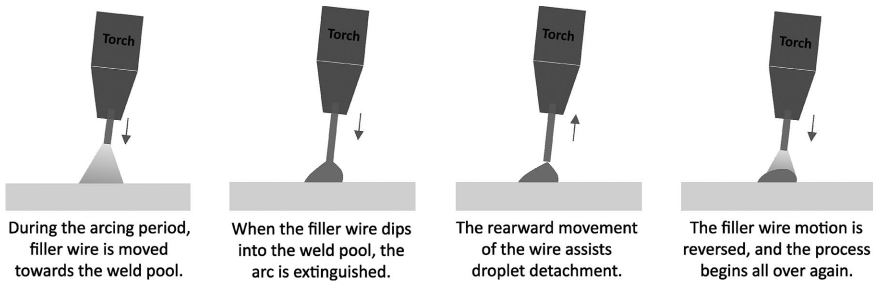

Figure 12.5 The principle of CMT process.

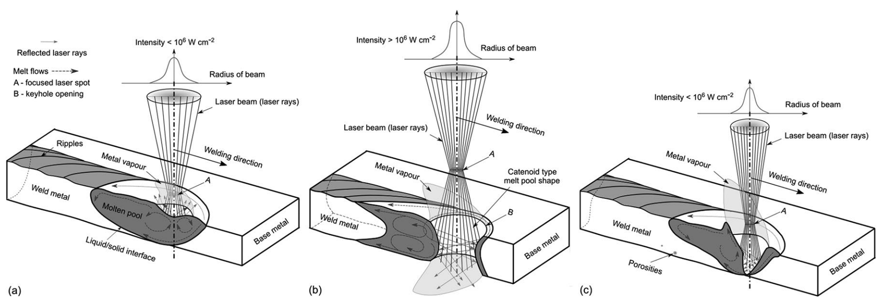

Figure 12.6 Laser beam welding operation types: (a) heat conduction mode; (b) keyhole mode with defocused laser; and (c) keyhole laser welding with highly focused energy.

process can be used for a wide range of materials and applications, e.g., automotive, industrial plant and pipeline construction [20].

Laser beam welding

LBW has been widely used in the automotive and aerospace industries for many decades and is well established for thin sheet joining. With recent developments in laser beam sources and automation, its use is rising. LBW is a complex fusion joining process where many electromagnetic waves strike the surface of the metal workpiece in a confined, tiny spot. Upon striking, a coherent stream of electromagnetic waves is partially absorbed by the base metal that generates heat, which melts the material, while the rest is reflected. LBW may operate in two different modes, the heat conduction mode and the keyhole mode, which depend on laser beam density. During high focusability with a small spot diameter (200–800 μm) and a high power density (>10^6 W/cm^2) [21], a vapor-filled cavity is created, termed the keyhole, that provides high penetration depths. The different modes and configurations during LBW are shown in Figure 12.6.

There are different laser types available. They can be classified by wavelength, temporal mode type (continuous wave or pulsed), mode type (single-mode or multi-mode) and emitting laser beam power output (low or high) with different optical parameters. Most widely used are solid-state fiber or disk laser systems, which provide a power output reaching 20 kW. One of the most significant advantages of these laser systems is their high energy efficiency, robustness and flexibility. High laser powers are usually multi-mode type, have lower focusability than single-mode type and are more used for thicker than 2 mm components. Single-mode fiber lasers can have as small as 10–20 μm focus spot diameters, which are excellent for micro-welding applications for highly reflective materials, such as in the battery industry. Recently, blue and green lasers have emerged with wavelengths of 450 μm and 550 μm, respectively, which offer much higher absorptivity than traditional fiber or disk lasers [22]. The pulsed mode is often used in joining highly conductive and reflective metals. The pulsing capability of laser sources is non-comparatively wider than in arc welding. Thus, it may offer higher-quality welds with lower defects. Filler wires can be added under the laser beam, and this may refine the microstructure and increase bridge ability when the air gap is opening to avoid drop-outs.

Laser-assisted arc welding

LAAW or laser-arc hybrid welding is a combination of the laser beam with an arc heat source within the same melt pool. Usually, the arc is located closer to one of the base metals, e.g., aluminum alloy, to melt a higher portion, while the laser beam is located closer to the interface since it is more concentrated and ensures metallurgical bonding between two dissimilar metals. LAAW is more commonly used nowadays and offers many advantages over autogenous LBW and even LBW with filler wire, e.g., improved process control, stability and quality of the joints. If MIG is combined, it offers an inherently simple filler wire addition to the weld pool. Due to the more extensive melting, the wettability and spreading distance of aluminum alloy are improved, which may provide improved strength of the joint. However, this process is much more complicated than autogenous LBW due to the large number amount of process parameters involved and the higher investment costs. Moreover, the heat input should also be limited to avoid excessive thickness of the IMC layer.

Comparison framework

This chapter supplies a technology mapping and comparison framework to support manufacturers in making decisions for the manufacturing of MMPs. As described in Section “Introduction”, five main performance categories for comparison have been selected. Under each main category, we also defined sub-categories as well as scales (1–5) for ranking. The ranking criteria are defined based on published and unpublished knowledge on welding aluminum to steel. The defined categories and descriptions are shown in Table 12.1.

Design flexibility

This sub-category is aimed at evaluating the design flexibility of different welding technologies, such as type of joint geometry, base material thickness range and limitation of materials that can be welded, among others. The comparison of different welding technologies is shown in Figure 12.7.

CMT technology is a more balanced process with respect to the defined criteria for design flexibility compared to the other techniques. It has excellent gap-bridging ability and excellent control over the deposited weld metal. All these features allow CMT welding to offer great flexibility in terms of material combination, thickness and joint geometrical design. LBW and LAAW systems offer high flexibility, as reflected by the wide range of possible welding parameter settings. Despite this, the parameters need to be optimized to achieve high-quality joints, and this can be a time-consuming process. Laser power output may have a wide range, and a single laser system can be used for different thicknesses. For the joining of dissimilar metals where high-reflectivity metals are present, such as aluminum and copper alloys, the wavelength can be adapted through recent developments. Moreover, due to its highly concentrated energy, LBW is an excellent choice for highly conductive materials. Consequently, LBW and LAAW offer much lower heat inputs and may achieve low distortions, which often occur in welding thin sheets. Lower heat inputs may decrease the width of the HAZ and, thus, the extent of softening zones in precipitation-hardened aluminum alloys.

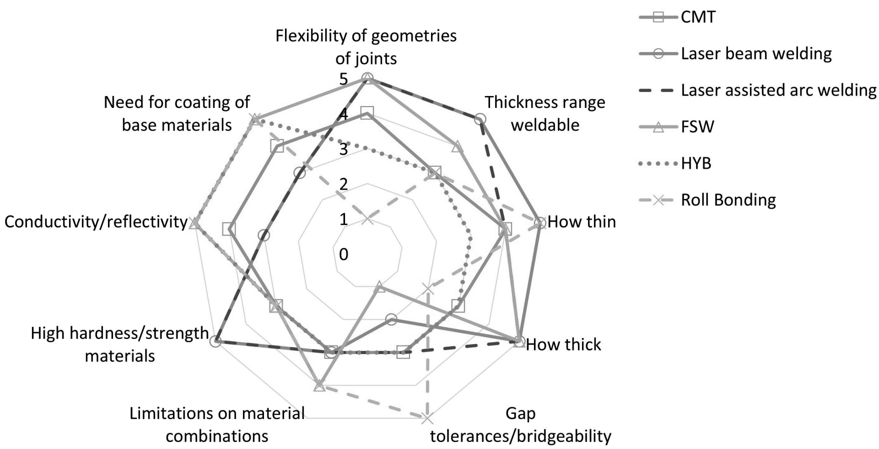

Figure 12.7 Design flexibility offered by the different welding techniques.

Table 12.1 Categories and scales for comparison [1, 6, 7, 17], and each category has five different levels of quality. Some categories may have three quality levels for simplicity.

Scale	*1 (Low/Poor)*	*2*	*3*	*4*	*5 (High/Best)*
Category 1: Design flexibility					
Flexibility of joint geometries (lap, butt, fillet/corner, edge, spot)	Restriction to one type of geometry	Possibility to weld two types of joints	Possibility to weld three types of joints	Possibility to weld four types of joints	Full spectrum of joints
Weldable thickness range	Limited to a narrow range: +/− 1 mm	Range within: +/− 2 mm	Range within: +/− 4 mm	Range within: 1–10 mm	A whole range 0.1–20 mm
How thin	Min. >= 2.0 mm	Range within: 1.5–2.0 mm	Range within: 1.0–1.5 mm	Range within: 0.5–1.0 mm	Range within: 0.1–0.5 mm
How thick	Max. 1 mm	Max. 1–2 mm	Max. 5–10 mm	Max. 10–15 mm	>20 mm
Gap tolerances/bridging ability	Poor, requires strict tolerances for tight setup	-	Moderate, allows a slight air gap opening	-	High allowance for air gap opening/closure
Limitations on material combination	Severely restricted	Narrow choice of materials	Moderate restriction	Wide choice of materials	No limitations
Limitations on high hardness/strength materials	Severely limited	Strict limitations	Moderate limitations	Low limitations, hard metals can be joined	No limitations (regardless of quality)
Limitations related to conductivity/reflectivity	Severely limited to low conductive/reflective metals	Strict limitations	Moderate limitations	Highly conductive/reflective metals are joined	No limitations
Need for coating of base materials	Required	-	-	-	Not required

(*Continued*)

Table 12.1 (Continued)

Scale	*1 (Low/Poor)*	*2*	*3*	*4*	*5 (High/Best)*
Category 2: Productivity					
Level of automation	Fully manual process and material handling	Semi-automized process or material handling	Automized process or automized material handling	Fully automized process and material handling	Fully adaptive manufacturing/ digital twin
Need for downtime and maintenance	High	-	Moderate	-	Low
Welding speed limits/ processing time	Max. 0.5 m/min	Max. 1.0 m/min	Max. 2.0 m/min	Max. 3.0 m/min	>3.0 m/min
Category 3: Quality					
Consistency of quality	Low	-	Moderate	-	High
Porosity	High	-	Moderate	-	Low
Lack of bonding	High	-	Moderate	-	Low
Hot cracking susceptibility	High	-	Moderate	-	Low
Particles/oxides	High	-	Moderate	-	Low
Required material/ surface preparation	Proper cleaning, suitable roughness and use of chemicals (fluxes)	-	Restricted only to surface roughness and cleaning	-	Only cleaning with acetone (standard procedure)
Mechanical properties in multi-material joints	<40% strength of the softer base material, e.g., aluminum	40–50% strength of the softer base material, e.g., aluminum	50–60% strength of the softer base material, e.g., aluminum	60–70% strength of the softer base material, e.g., aluminum	>70% strength of the softer base material, e.g., aluminum

Category 4: IMC formation and mitigation strategies					
Typical thickness of brittle intermetallic layer, morphology	>10–12 microns, irregular shape	-	3–10 microns, quasi-regular	-	<2 micros, regular/ continuous
Possibility of modification and control of IMC through alloying filler wire or intermediate layer	Strictly limited	-	Limited possibilities	-	Full possibilities
Category 5: Technology accessibility and maturity					
Technology readiness level	Applied research (TRL 2–3)	Laboratory testing (TRL 4–5)	Prototype system verified (TRL 6)	System incorporated and (TRL 7–8)	Commercially available (TRL 9)
Investment cost (EUR 1000)	Very high (>500). e.g., 20 kW fiber laser	High (500–200). e.g., FSW or low power fiber laser	Moderate (100–200). e.g., FSW or low power fiber laser	Low (up to 100). e.g., CMT arc source	Very low (<20). e.g., MIG
Operating costs	Very high	High	Moderate	Low	Very low

Moving on to solid-stage welding, roll bonding offers little to no limitations regarding material combinations to be joined, and thus, complex composite structures consisting of several different metals can be produced within a large range in thickness. However, the technique is mainly suitable for producing dissimilar metal products in the form of sheets, strips, foils, plates or cladded plates. Thus, the combination of rolling with subsequent metal-forming processes such as drawing or bending is necessary to produce more complex shapes and products. FSW offers large flexibility with regard to joint design and materials combinations that can be joined together [15]. However, for welding thick plates and structures, high requirements are set on the necessary equipment to provide a sufficient amount of pressure and sufficiently high rotational speed. Other disadvantages are related to the experienced wear of the FSW tool during the welding of high-strength and high-hardness materials. In addition, the technique has low flexibility concerning gap tolerances. The HYB process, with its possibility to add filler materials, can offer flexibility in terms of geometrical design freedom, edge- and surface-preparation, as well as gap and misalignment tolerance. The addition of filler material also provides a competitive advantage over other solid-state joining processes in terms of increased design flexibility and tolerance, reduced need for preparation and improved joint properties.

Productivity

Productivity is a key criterion when selecting a suitable technology for welding dissimilar metals. Many factors affect productivity at different levels, from pilot to a full production line, such as the automation level of the process and material handling, welding speed and the need for downtime and maintenance. HYB and FSW have relatively lower welding speeds compared to CMT, LBW, LAAW and roll bonding processes. For FSW, the tool wear limits the welding speed, lowering productivity, especially for high-hardness/strength materials. CMT, with its improved weld quality, reduces post-production rework, leading to an increase in manufacturing and efficiency. The CMT process has a high deposition rate and can achieve deep weld penetration as well as high welding speed. The high focusability of LBW/LAAW offers high penetration depths due to the keyhole. This may provide much higher welding speeds compared to conventional arc welding and can be up to 10–20 times faster, depending on process parameters.

In general, commercially available welding processes have higher levels of automation. Roll bonding can be easily automated and does not require the use of shielding gas, additional material such as filler wire or large energy consumptions. The HYB technology needs to be further developed to make it suitable for flexible manufacturing of MMPs and installation in an industrial environment. However, in the future, there is a large unexploited potential for improving the productivity of the HYB process through robotization.

Quality

How to achieve consistent welding quality is of undeniable importance for the selection of welding technologies. In this sub-category, we compared different welding methods with respect to the mechanical properties of the welded joint in proportion to the strength of the softer base material, e.g., the strength of the aluminum base material in an aluminum-steel joint. In addition, we also focused on potential defects in welds, e.g., porosity, lack of bonding, hot cracking and the formation of particles and oxides, among others. The comparison is shown in Figure 12.8.

Based on the conducted evaluations, it seems that solid-state welding methods, especially HYB and FSW, can achieve the best mechanical properties [23]. When it comes to welding aluminum and steel, solid-state welding methods cause less porosity in welds. However, porosity is a major challenge for fusion-based methods such as CMT and laser welding. The CMT process improves weld quality by reducing distortion and spatter due to reduced heat input compared to conventional GMAW. This also applies to LBW and LAAW, where low heat inputs promote a thinner intermetallic layer, which is positive for the mechanical properties. For roll bonding, the final quality and strength are strongly dependent on the material surface preparation [24]. The quality might thus vary if the surface preparation is not performed optimally across the entire interface to be joined. Thus, performing roll bonding at an industrial scale is challenging without the use of a protective atmosphere, especially when working with metals with a high oxygen affinity at high temperatures. Compared to the other techniques, the bond strength between the joined base materials of roll-bonded MMPs is often lower than for other techniques and is not easily measured in multi-layered composite structures. FSW is also susceptible to welding defects, such as lack of bonding or tunnel defects, when welds are produced

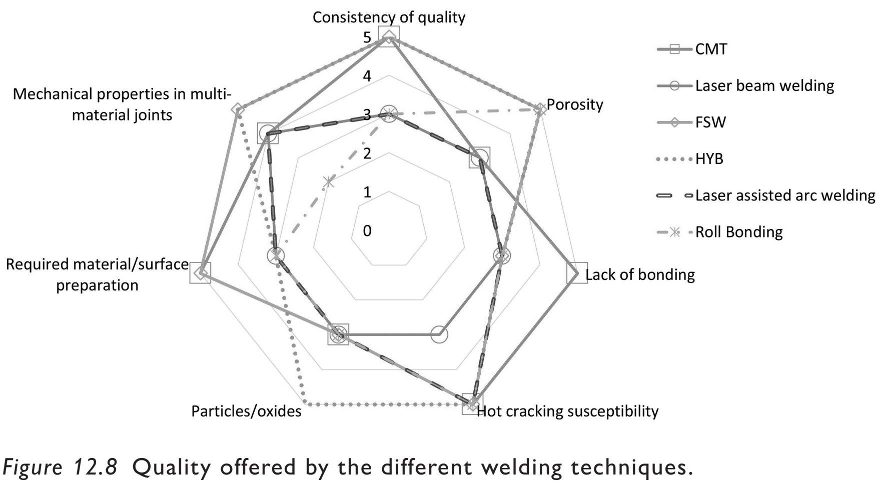

Figure 12.8 Quality offered by the different welding techniques.

with sub-optimal process parameters. However, when the welding process is stable, high-quality joints can be produced without defects.

IMC mitigation strategies

As already stated, the IMC layer dominates the dissimilar material weld properties. In this category, we focused on the effect that different welding processes have on the thickness of the IMC layer, its morphology and embrittlement. The welding heat input plays an important role in the formation of IMCs. Therefore, solid-state welding methods (roll bonding, HYB and FSW), in general, produce a thinner IMC layer compared to fusion-based welding processes [10, 25, 26]. However, CMT is still suitable for welding dissimilar metals due to its unique feature of low heat input compared to conventional arc welding [27]. This also applies to laser-based welding processes. The processes involving the addition of filler material, in general, are more feasible when it comes to modification of the nature of the IMC layer, as mentioned previously in Section "IMC – characterization and mitigation strategies". Roll bonding has more advantages in terms of adding an intermediate layer due to its process feature. The HYB process can add a filler metal that can also act as an interlayer, which can reduce the risk of interfacial cracking and thus improve the mechanical properties. In addition, it is also possible to tailor the properties of the filler material to optimize the properties of dissimilar metal joints. LBW offers a much-extended control over the thermal cycle inputs compared to other joining methods by allowing manipulation of the optical parameters. However, it can be challenging to add filler wire under the laser, requiring additional optimization. LAAW offers more flexible solutions through the addition of a filler wire.

Technology accessibility and maturity

The technology accessibility and maturity were evaluated for three aspects, i.e., technology readiness level (TRL) [28], investment cost and maintenance cost. It should be noted that some of the studied welding technologies are still under development, even though they have relatively high TRL levels, like HYB. However, HYB has not yet been implemented at the industrial production level, and thus, it is difficult to estimate the investment cost and operating costs. Although HYB is a promising welding technology for welding of dissimilar metals, its accessibility is regarded as low. In contrast, roll bonding is a well-established and inexpensive manufacturing process that has relatively higher technology accessibility and maturity. FSW is a fully industrialized process that can be fully automated, reducing operating costs such as labor costs. Moreover, significant savings can be realized due to the considerable reduction in repair and rework, low distortion of produced joints and general equipment flexibility. However, the investment in new FSW equipment could be expensive.

CMT welding is commercially available and has been widely applied in a wide range of industry applications. However, the cost of the CMT system is somewhat higher than that of the conventional GMAW system. Moreover, the CMT technology is relatively new and constantly under development, which may impose some challenges for operators. Therefore, the operating cost may be higher compared to other widely used welding systems.

Laser systems are usually fully or partially automated since they require high precision and high capital investments. However, they are strongly competitive in mass production and especially in joining thin sheets used in the automotive industry, where LBW systems almost fully substitute conventional arc welding and have a high degree of automatization. The operating costs can be considered to be low in such cases.

The technology mapping

This subsection summarizes the comparison of the selected welding technologies in terms of five defined main categories. The ranking is based on the average score of sub-categories under each main category. It should be noted that no weighting of sub-categories has been used for this comparison. We would like to emphasize that the purpose of this chapter is to supply a qualitative rather than quantitative comparison of different welding technologies due to the fact that the selected welding technologies are based on quite different physical principles and have reached different TRLs. Moreover, the comparison has been made based on limited published and unpublished data and the knowledge of the authors on each welding technology. The mapping may not reflect the full picture of reality. However, we do believe this comparative study can supply useful information and provide a knowledge basis for selecting the proper welding process in the manufacturing of dissimilar metallic components. The technology comparison is shown in Figure 12.9.

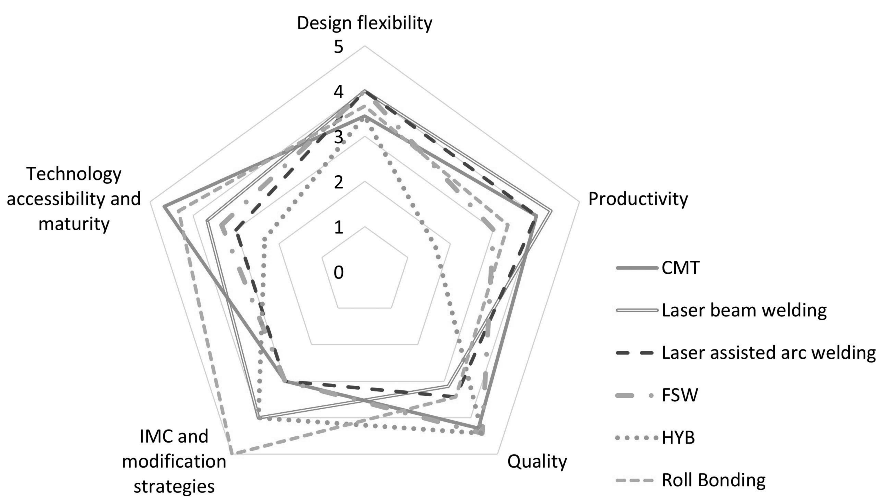

Figure 12.9 The technology mapping of the selected welding technologies.

Obviously, all investigated welding methods can offer good design flexibility. HYB, FSW and CMT can achieve better quality than other welding technologies. Commercially available technologies have relatively higher productivity than technologies under development. When it comes to technology accessibility and maturity, commercial technologies (CMT and LBW/LAAW) and well-established technologies (roll bonding) have advantages over other technologies. In terms of IMC and mitigation possibilities, all technologies have the possibility to control and modify the IMC to a certain extent. However, it seems that roll bonding technology can outperform other technologies when it comes to control and modification of the properties of the IMC layers.

Sustainability and circularity of multi-material products

Sustainability in manufacturing is a topic of great importance in the ongoing green transition. In addition to the aspects discussed within this chapter, such as design flexibility, productivity and quality, sustainability should be an essential part of the evaluation and comparison of the suitability of welding techniques for multi-material joining. In general, sustainability in manufacturing and for a given manufacturing process such as welding can be evaluated based on the three developed dimensions: environmental development, social development and economic development [29]. Hence, a sustainable welding method should, for instance, have minimal energy consumption, high process efficiency, minimal use of resources and generation of material waste, in addition to offering a safe work environment. Already, the sustainability of welding processes has been evaluated and discussed in detail [30]. Saad et al. [31] established a general but comprehensive framework for assessing the sustainability dimensions of selected welding techniques, where each of the defined dimensions was evaluated according to a set of sustainability indicators. Mehta [30] concluded that solid-state welding technologies are found to achieve a high score on sustainability compared to fusion welding techniques. This is due to the elimination of arc, fumes and the use of shielding gas, in addition to the reduced risk of defect formation and distortion of the final product.

The concept of a circular economy is essential in promoting sustainable development. Recycling, reusing and repurposing are just some of the known 10R strategies for promoting a circular economy [32]. The single most important contribution to the welding of MMPs in terms of sustainability is to produce joints that can sustain a long service time. This will provide for products qualifying for the upper region of the 10R circular strategies (R2–3) based on a prolonged product lifetime and, hence, a reduction in the use of materials. Furthermore, a weld joint with a potential long service time can also be very valuable for remanufacturing into new products after the first product lifecycle and thereby also contribute to circular strategies in level R3–7. Below this level, recycling is the most adequate circular option. Metals are recyclable and can be remelted and reused without experiencing degradation of properties, promoting the principles of circular economy. However, the mechanical properties of metal alloys are sensitive to the presence of impurity elements. Thus, post-consumer scrap and unsorted metal products are often not recycled and utilized in most products that require certain performance and properties. It is currently very challenging to separate the welded, dissimilar metal components, especially if they are firmly bonded together by an IMC layer. The focus of this chapter is on the comparison of different welding technologies that are suitable for the production of MMPs of high quality. It is indeed difficult to make a quantitative sustainability comparison of different welding methods. However, we would like to emphasize that sustainability and circularity are important factors that need to be considered when designing MMPs and selecting a relevant welding technology in the future.

Summary and perspective

This chapter has described and evaluated six welding technologies that have been studied within SFI Manufacturing. These welding technologies are regarded as suitable for the manufacturing of high-performance MMPs. The chapter presented the basic principles of each welding technology and compared them in five main performance categories. The formation of IMC is a crucial issue for the welding of dissimilar metals. Therefore, we also described the mechanisms of the formation of IMC and possible mitigation strategies in this chapter. We highlighted the importance of considering sustainability and circularity in the design and manufacturing of MMPs, although this has not been a part of the benchmarking of the different welding technologies. It is not the objective of this chapter to supply a comprehensive technological overview of each welding technology. However, we do hope the knowledge-based comparison framework presented in this chapter can support the industry in choosing the most suitable welding method to produce MMPs. As MMPs become more and more attractive, joining technologies, including welding, should be further developed. The following research and development perspectives are proposed:

- Further development of advanced material characterization technologies, e.g., atomic force microscopy (AFM) and transmission electron microscopy (TEM), combined with a multi-material modeling framework to better understand the formation mechanism of the IMC and supply the knowledge basis for tailoring and modifying the IMC to achieve high-performance dissimilar weld joints. A combined experimental-numerical approach will be very useful in terms of materials selection as well as the development of new alloys and welding processes for the targeted dissimilar metallic weld joints.

- Develop new joining processes, such as additive manufacturing (AM) [33], or develop innovative joining processes by combining the advantages of different welding methods, e.g., laser-assisted FSW [34].
- Develop and implement a design-for-sustainability concept in the design and manufacturing of MMPs, where the possibilities to recycle and reuse MMPs should be further investigated.
- Standardization of the welding methods for dissimilar metallic metals should be pursued in the future with a joint force between research institutes, industry partners and standardization organizations.

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Chapter 13

A review of recent advances in additive manufacturing with polymer materials

Ben Alcock and Erik Andreassen

Introduction

Additive manufacturing with polymer-based materials

Additive manufacturing (AM), often referred to as 3D printing, is a class of processes for joining materials to make parts directly from a digital 3D model, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies [1]. Many AM process categories [1] utilise polymer-based materials and composites.

Because AM does not require tooling, one advantage of AM is to make part series with customised geometries ("mass customisation"). Another advantage of AM is the geometrical freedom, and parts should be designed/redesigned to leverage this, e.g., by replacing a multi-part assembly by a single part ("part consolidation"). The geometrical freedom can also be utilised for reducing the part weight, e.g., by optimising the geometry for a given load by computational design methods such as shape and topology optimisation or by integrating lattice structures into the part design.

Polymer AM has traditionally been used for prototypes and models, and these are still important applications, for example, as models to aid in the planning of surgical procedures. However, there is a trend towards making production tools (moulds, fixtures, grippers, etc.) and end-use parts in small to medium volumes by polymer AM. One important application is spare parts that can be made on-demand and on-site, and AM-based supply chains are being established [2,3], e.g., for the railway, shipping, oil & gas and defence sectors. Polymer AM spare parts can, e.g., be valve handles, pump fans and covers/enclosures. The selection of spare parts that are suitable for AM supply chains is complex. Cardeal et al. [3] identified factors such as the age of the component, the frequency of demand, the criticality of the component and its value and lead time uncertainty.

AM is constantly evolving. According to the European Patent Office (EPO) [4], AM has experienced eight times faster growth than the average of all technologies. Patent families related to AM grew at an average rate of 26.3%

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per year from 2013 to 2020. However, many AM processes are also relatively mature, but industrial implementation for manufacturing is limited [5] and technological advancement is no guarantee of widespread industrial adoption. In a 2022 white paper [6], several potential challenges to the adoption of AM are identified, in technical areas (e.g. related to available materials or the performance of equipment) and non-technical areas (e.g. adoption of AM within companies and the economic viability of AM processes).

Several researchers [7–11] have recently presented assessments of the adoption of AM in different industries and different geographical areas. While a clear advantage of AM over conventional manufacturing is a requirement for the industrial adoption of AM, the nature of the advantage over conventional manufacturing varies between manufacturers. Common examples of the advantages of AM, which are the drivers of industrial adoption, are reducing labour costs, reducing time to market, increasing part complexity, or making available otherwise obsolete parts. Conversely, common concerns that oppose industrial adoption are the predicted costs, quality and accuracy of additive manufactured polymer parts [12], compared to equivalent parts produced by conventional manufacturing, such as injection moulding. As well as the properties of the parts, the adoption of industrial AM affects the entire supply chain [13]; for example, reduced time to market enables production to start after purchase [14], which can reduce the costs associated with larger inventory volumes pending purchase.

Rauch et al. [15] suggested the 20 most promising industrial sectors for the adoption of AM in European industry to include a diverse range of manufacturers of medical equipment, jewellery, aerospace, footwear, sports equipment and motor vehicles, although it is clear that not all of these industries will include polymer-based materials. Already in 2014, the AM machine producer Stratasys made more than 1,000 AM polymer parts for the first-of-type Airbus A350 XWB aircraft, and in 2021, Stratasys was awarded a contract to produce polymer cabin interior components for several Airbus aircrafts (replacement and spare parts) [16]. The need to quickly establish new production lines for polymer parts was demonstrated during the COVID-19 pandemic [17]. AM enabled the supply of large volumes of components for medical products such as facemasks, respirators and nasal swabs, produced locally at shorter time scales than would otherwise have been feasible using other manufacturing routes. Wiese et al. [18] reported a systematic review of polymer materials and processes specifically for the automotive industry and identified combinations of materials and AM processes matching automotive applications.

As well as different adoptions in different manufacturing industries, the adoption of AM varies geographically. For example, a recent investigation reported estimated variations in adoption of AM even between neighbouring European countries [11]. Considering that industrial AM also enables more localised manufacturing, closer to the market, these geographical variations in AM adoption will likely correspond to the geographical variations in manufacturing industries.

Many AM processing routes have been developed for a wide range of polymer materials. It is clear that AM processes for producing polymer parts can find applications in many different market segments. The requirements of the parts will define the polymer materials to be used and therefore limit the AM processes to those that are compatible with these polymers.

Additive manufacturing process categories and outline of the chapter

The motivation for this review is the development towards industrial use of polymer AM, i.e., making parts that can fulfil demanding specifications with regard to, e.g., mechanical properties and geometrical tolerances. The production time per part is also an important factor. Most of this review is based on scientific literature, but technological and practical aspects are also included.

The two main sections of this chapter ("Material extrusion (MEX)" and "Powder bed fusion (PBF)") review the two most important industrially applicable AM process categories for thermoplastic polymers: MEX [1] and PBF [1]. Two other relevant AM process categories, vat photopolymerisation (VPP [1]) and material jetting (MJT) [1], are covered briefly in the section "Other industrially relevant polymer AM process categories: vat photopolymerisation (VPP) and material jetting (MJT)".

These AM processes can, to some degree, replace conventional polymer processing methods such as injection moulding. MEX is the most widespread polymer AM process in terms of printers installed (due to the low entry cost), but PBF and VPP may have higher potential for large production volumes and low cost per part (although MEX-based "print farms" can also be competitive). Regarding polymer materials for AM, "photopolymers" for VPP (and some other AM processes) have been the largest group in terms of sales (revenue) for three decades [19]. However, since 2020, polymers for PBF have overtaken photopolymers [19].

The section "Material extrusion (MEX)" presents MEX and starts with an overview of machines, software, materials and printing parameters. Due to the high publication rate in the polymer MEX field (as summarised in the sub-section "Overview of the scientific literature"), we have chosen to write some parts of the section "Material extrusion (MEX)" as an "overview of reviews". Furthermore, rather than reviewing a large number of findings which are often not generalisable (as discussed in the sub-section "How generalisable are the results from printing parameter studies?"), we outline the generic defect mechanisms (such as voids/gap and internal stresses) and their consequences. The section "Material extrusion (MEX)" also summarises discussions regarding the cause of the often reported high anisotropy in tensile properties (In the sub-section "What is the cause of the reported high anisotropy in tensile properties?"). After presenting the background and defect mechanisms in several sub-sections, the sub-section "How to improve the mechanical properties and reduce the anisotropy?" reviews literature on how mechanical properties can be improved, while the sub-section "Material-focused studies and challenges with semi-crystalline materials" summarises some material-focused studies. The sub-section "Improving part quality and repeatability by implementing monitoring and control systems" deals with monitoring and control systems, which are key technologies to improve part quality and repeatability. Finally, The sub-section "Scalability (part size and productivity) in an industrial context" addresses some aspects of scalability (part size and printing speed). Finally, the MEX section is summarised in the sub-section "Summary and industrial perspective for MEX technologies".

The section "Powder bed fusion (PBF)" starts with an overview of PBF processes, machines and materials, as well as published literature. The sub-section "Properties of PBF parts" briefly summarises quality aspects, while the sub-section "Factors affecting industrial implementation of PBF" deals with the industrial implementation. Finally, possibilities for manufacturing multimaterial components are reviewed in the final sub-section.

The section "Other industrially relevant polymer AM process categories: vat photopolymerisation (VPP) and material jetting (MJT)" briefly summarises two other industrially relevant AM process categories for polymeric materials: VPP [1] and MJT [1]. Like MEX and PBF, VPP can also be used for end-use parts with demanding requirements, and there are many interesting VPP developments. However, due to the limited space in this chapter, we have chosen to focus on thermoplastics (VPP uses thermosets) and only included a short VPP section for completeness. MJT with thermoplastic materials can achieve good part properties, but this process has few machine installations compared to MEX and PBF.

Finally, the section "Sustainability" addresses some of the main aspects of the sustainability of AM with thermoplastic polymer materials.

Material extrusion (MEX)

Machines, software, materials and printing parameters

The most common AM method for thermoplastic polymer materials, in terms of installed machines, is MEX with filaments as feedstock. The ISO/ASTM standard term MEX [1] is used in this chapter. However, many names (some are registered trademarks) are used for this filament-based process, such as fused filament fabrication, filament freeform fabrication and fused deposition modeling (FDM).

The general principle is that a solid filament (the most common diameter is 1.75 mm) is fed, e.g., with a pinch roller mechanism, into a heated nozzle, which melts the (thermoplastic) material and extrudes it to build the part layer by layer (Figure 13.1). The entire unit responsible for the extrusion, including the nozzle, fans, etc. (from Figure 13.1c–f), is usually referred to as the print head, while only the top "cold" feeding part is called the extruder. However, some also use the term extruder or extrusion head for the entire unit.

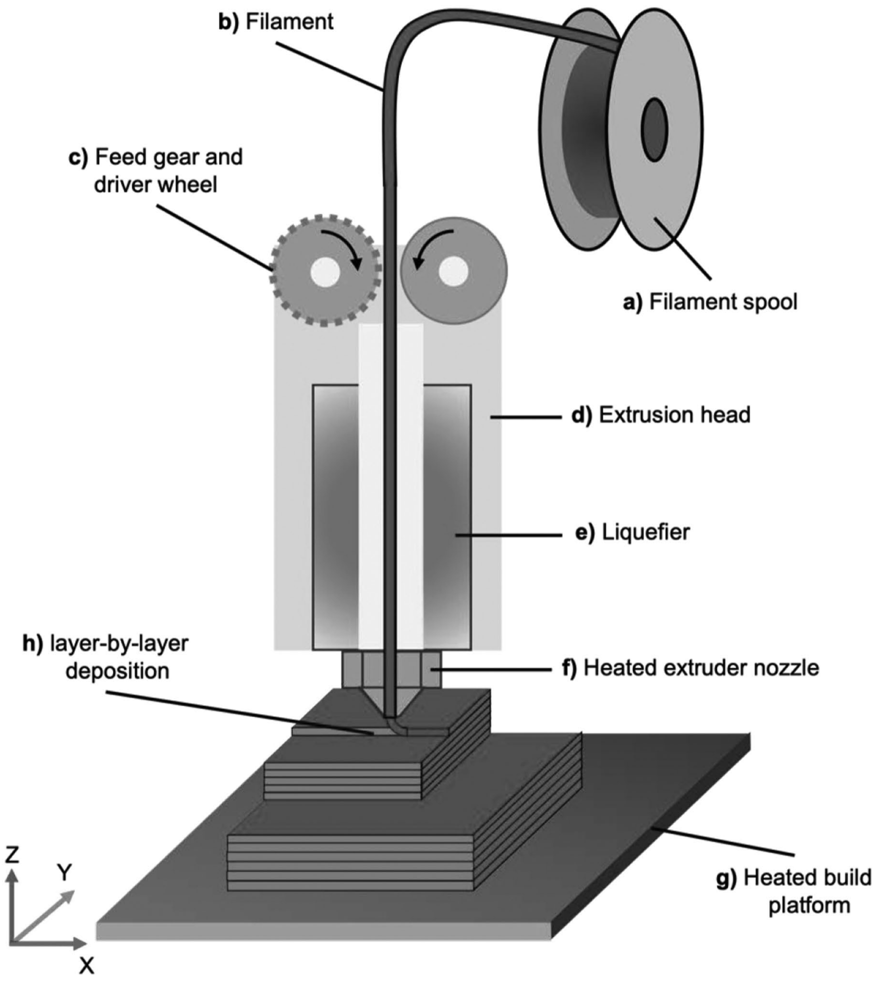

Figure 13.1 Illustration of the polymer MEX process with filaments as feedstock. The extrusion head (also referred to as the print head) and the build platform are moved relative to each other. Figure reproduced from ref. [25] (CC-BY license).

The deposited extrudate is slightly wider than the nozzle diameter (typically in the range 0.25–0.8 mm), and the layer thickness is typically 50–75% of the nozzle diameter; see also Table 13.1. A distinguishing feature for such printers is whether they have an actively heated build chamber or not. A chamber with a controlled elevated temperature reduces thermal gradients in the part during printing (thereby reducing thermal stresses that may cause warpage and delamination) and may improve the adhesion between layers. Especially for high-temperature materials, such as PEEK, a heated chamber is essential [20]. Furthermore, the printers have different solutions for moving the print head with the nozzle relative to the build platform ("kinematic design"). Different kinematic designs [21–23] have their pros and cons when it comes to speed, vibrations, accuracy, scalability, footprint, complexity and cost. Then there are different options for motors (e.g. stepper vs. servo motors) and transmissions. Most printers have three independent Cartesian axes (with the nozzle always pointing perpendicular to the build platform), but there are also printers with additional axes, which enable true non-planar printing paths, as well as printers with other axis systems [24] than Cartesian, e.g., delta printers.

There are also MEX printers that use pellets (granulates) as feedstock instead of filament. In principle, such printers can then use standard pellets meant for conventional extrusion or injection moulding of thermoplastic materials ("plastics"). This reduces the material cost and improves the carbon footprint, as the filament production step is avoided (however, filaments can also be produced directly without going via pellets). Pellet extruders for 3D printers can be small versions of conventional single screw extruders. As these extruders are still much heavier than filament extruders, pellet-fed 3D printers are usually large, with high throughput and a large extrudate diameter. Hence, such processes are often referred to as big area AM (BAAM) or similar terms. Due to the larger nozzle, the printed parts are coarser, and sometimes the machines are hybrids; after the printing, the extruder tool is replaced with a machining tool, so that the final shape and surface finish are obtained by machining. There are also some small pellet-fed printers for technical parts, which give similar tolerances and surface finish as filament-fed printers. Elastomers are easier to process with a pellet extruder [26] than with a typical filament extruder because a soft filament (e.g. below 70 Shore A) may jam in a filament extruder.

This section reviews MEX with thermoplastic filaments, although there are many similarities with pellet-fed MEX. For simplicity, we will use the term MEX in this section. Note that other materials than thermoplastics can also be processed as MEX with appropriate extruders and mixing units, e.g., thermosets such as silicone rubber and polyurethane (often referred to as reactive MEX).

The so-called slicer software also plays an important role for the part properties. This software converts the digital 3D model into a file with all the instructions for the printer (referred to as G-code). The G-code describes

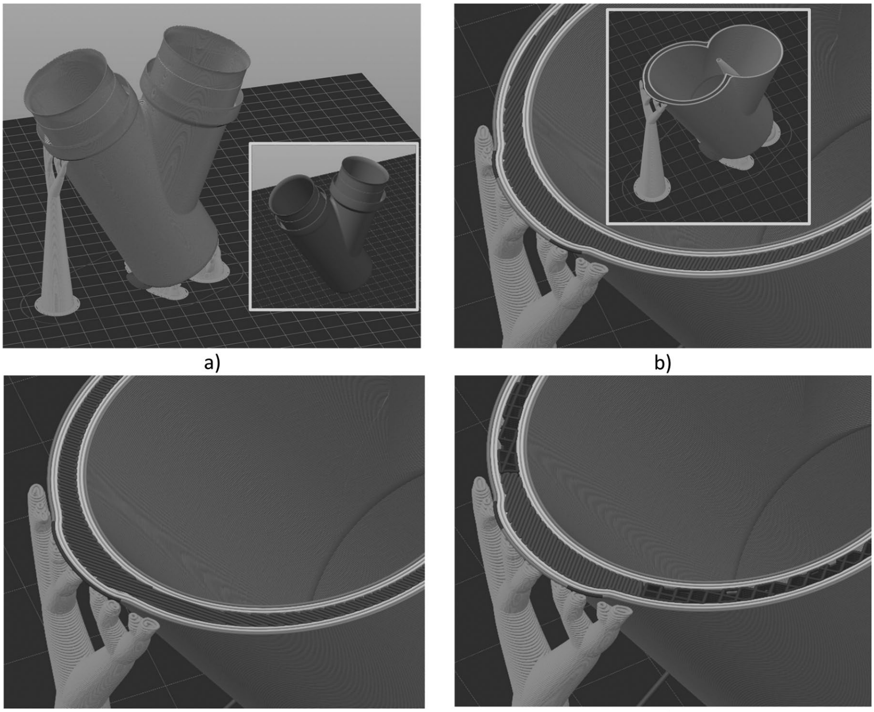
a) b) c) d)

Figure 13.2 Illustrations of output from slicer software (PrusaSlicer 2.6.0). (a) Sliced part on the build platform, with external and internal support structures. The insert shows the part before slicing. (b) A cross-section of the sliced part, with contour strands and infill strands ("100%" density). (c) The layer beneath that in (b), with a perpendicular raster angle. (d) Same cross-section as in (b), but here the part is sliced with a 50% infill. Still, the software has chosen to use 100% infill in critical domains. Note that such "sparse" infill is more suitable for thicker parts than in this example.

the width and path of the deposited extrudate and the toolpath of the print head in each layer (see Figure 13.2), as well as speeds, temperatures and many other detailed settings, e.g., for accelerations. Furthermore, an important role for the slicer software is to generate "infill patterns" to print a part less than 100% solid, as well as support structures if needed (Figure 13.2). The deposited extrudate is referred to by many names in the literature, e.g., raster, strand and bead.

Turner and Gold [27] classified the printing parameters (the settings contained in the G-code) in three categories: design, process and toolpath parameters. Golab et al. [25] used a similar classification as well as a distinction between printers with and without a heated chamber; see also Table 13.1.

Table 13.1 Some of the main MEX printing parameters, adapted from Golab et al. [25]. The volumetric extrusion rate is not user input; it is calculated from other parameters. Some parameters may have special values for the first layer.

Design parameters: • **Build orientation** (the orientation of the part relative to the build platform) • **Infill pattern** (the internal structure of the part) • **Infill density** (100% means solid) • **Position in the build envelope** ***Process parameters:*** • **Extrusion temperature** • **Nozzle diameter** (nozzle type/geometry could have been a separate parameter) • **Bed temperature** • **Environment temperature** (for printers with a closed chamber)	***Toolpath parameters:*** • **Layer height** • **Volumetric extrusion rate** (for material extruded through the nozzle) • **Print head speeds for "contour" and "infill"** (i.e. the in-plane speed of the print head) • **Air gap** (distance between adjacent deposited extrudate strands; slicers usually deposit the strands with overlap, i.e. a negative air gap) • **Raster angle** (angle between the deposited strand and the (in-plane) X axis of the printer) • **Width of the deposited extrudate strand** (some slicers allow for variable width along the toolpath) • **Contour width** (typically defined as the number, or minimum number, of strands that define the contour of the part in a given layer; the strands in the contour may have different widths than those in the infill)

One advantage of MEX compared to other polymer AM processes is that there are many materials available as feedstock – almost all the thermoplastic polymer materials that are available for other processes. However, compared to injection moulding, MEX is more sensitive to material properties (rheology, solidification kinetics/shrinkage), which limits the material selection somewhat. The feedstock cost is also lower than for, e.g., PBF and VPP. MEX can also be used to print metal parts in a multi-step process [28]. First, a normal polymer AM printer is used to print a part using a filament with a high concentration of metal particles, and then this part goes through debinding and sintering steps to yield a near-100% metal part. Such filaments can be bought from, e.g., BASF, which also offers a network of debinding and sintering services.

MEX allows for multi-material prints (e.g. hard-soft combinations), either by having several print heads or by having a system for changing which filament is fed to the print head (during the printing process). A typical industrial MEX 3D printer (costing around EUR 5,000 and above) has two print heads [29], and the second print head is mostly used for printing the support structure (if needed), with a dedicated support material that can be easily broken off or dissolved, e.g., in water. MEX processes can also be paused for embedding components, such as threaded metal inserts (these can also be added after printing), metal bushings, carbon fibre reinforcement, or sensors.

For many years, MEX with filaments was synonymous with FDM technology from Stratasys, the company that invented 3D printing with filaments and sold their first 3D printer in 1992. Since the late 2000s, open-source movements such as RepRap have contributed to the development of MEX 3D printers, as well as software and firmware. “Open” means that printer design/component details, software and firmware codes are open for others to use and develop further, and also that the printers are not locked to certain filaments or software. Expirations of key patents have also opened for innovations and new companies in the field. Today, there are a wide range of MEX 3D printers available for professional use, with different capabilities and specialities. Some printers are made for certain applications (e.g. medical parts) or certain materials (e.g. high-temperature materials such as PEEK). Many printer manufacturers offer well-developed ecosystems (open or closed) with printers, materials (filaments) and software.

Last, but not least, MEX has the advantage that parts with good quality can be made with relatively inexpensive 3D printers, which are also robust and easy to maintain and repair. Schmidt et al. [29] recently compared 14 printers in the price range of EUR 440–44,000, using the material ABS and three test parts. For some part properties (such as the number of defects and tensile strain at break), there was a correlation with printer price, but for other properties (e.g. surface roughness, tensile strength and dimensional accuracy), no clear correlation was found. Furthermore, no clear correlation was found between the printer price and the standard deviation of the measured properties. The article concluded that several printers in the price range of EUR 1,000–5,000 could be used for industrial applications (at least with ABS). Birkelid et al. [30] described and validated an open-source hardware upgrade of a low-cost 3D printer, enabling it to print high-temperature polymers (with nozzle temperature up to 500°C, chamber temperature up to 135°C, build volume 500 × 500 × 500 mm^3), with a total hardware cost of EUR 1,700 including the low-cost printer.

Overview of the scientific literature

The importance of polymer MEX is reflected in the output of scientific literature (Figure 13.3), which increased considerably as research-friendly open printers became available about ten years ago. According to our literature search, more than 1,000 articles have been published each year since 2020, and about 330 review articles were published in the five-year period 2018–2022.

A multitude of topics are addressed in these publications. Many articles investigate relationships between printing parameters, post-processing parameters and part properties for various materials. This includes studies of

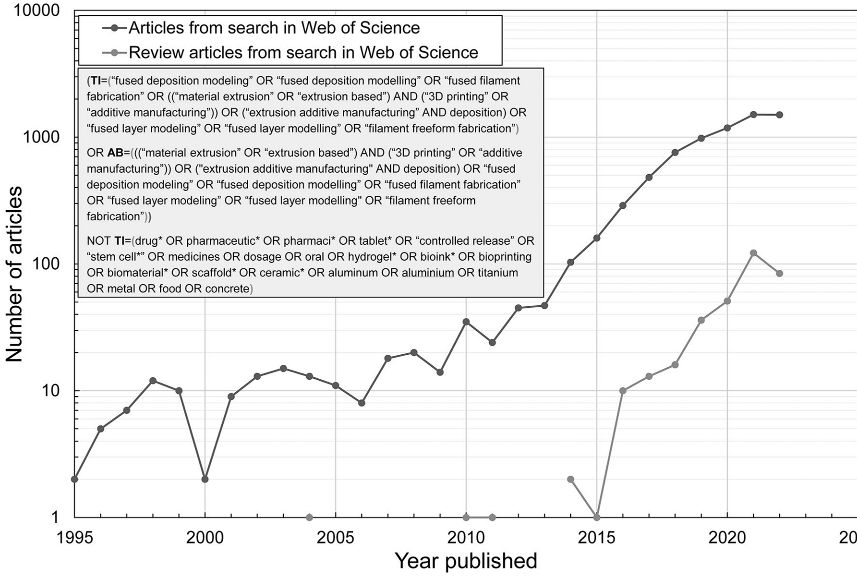

Figure 13.3 Results of a literature search for articles about polymer MEX in the database Web of Science [31] in February 2023. The search expression is given in the grey box (TI means article title and AT means article abstract). There is quite some literature on MEX of pharmaceutical formulations, often with polymeric materials. These articles have been excluded from the search, although some of them give valuable insight that is relevant for MEX of industrial parts with standard plastics. On the other hand, articles on medical applications such as implants and orthoses are included in the search. Articles on metals, ceramics and concrete are excluded. (In general, articles dealing with these materials would use other word combinations in the title and abstract than those in the first nine lines in the box above.)

slicing parameters and slicing algorithms. Some articles dive deeper into this by modifying or formulating materials, modifying printers or slicing algorithms, or developing numerical models. Many papers concentrate on the mechanical properties of the printed parts, some with advanced characterisation and analysis. Another key area is monitoring and control of the process and part quality. Another group of articles investigates certain applications of polymer MEX, e.g., exploring the geometrical freedom of AM via topology optimisation.

Among the about 7,400 articles in the search in Figure 13.3, about 70 have been cited more than 100 times (as of February 2023, but note that the majority of the papers are quite new, so the number of citations will increase). About half of these are review articles. There are also a few general AM reviews with a minor (but relevant) polymer MEX part that were not picked up by this search. If these are included and the 20 highest cited articles relevant for industrial polymer MEX are reviewed, about one third are on material-process-property relationships in general [27,32–38], one third focuses on composites [39–45], while the last third deals with certain specialities and applications such as microfluidics devices [46] and soft robotics [47].

Shortcomings of the process and typical part defects

A large number of the publications mentioned in the sub-section above address shortcomings and defects related to MEX, which we will summarise in the sections below.

Common topics are the low dimensional accuracy (often due to thermal stresses and warpage) and the rather large mechanical anisotropy, with apparently low strength and low strain at break in the direction perpendicular to the build platform (Z direction). One root cause of the low strength is unintended voids and stress concentrations arising from these, and other irregularities such as grooves between deposited extrudates. Other shortcomings include poor surface finish, low geometrical resolution and long printing time per part.

It has been noted [25] that due to the discontinuous and hierarchical nature of MEX, defects are innate to the process and are recurrent, and because of these inherent flaws, MEX has some limitations with regard to producing parts "right the first time" (which is important as typical production volumes are small).

In addition to the shortcomings listed above, some typical part defects were summarised (with cause, effect and references) in the review by Oleff et al. [48]: Bubbles and bulges (due to moisture in the filament), incorrect position of deposited strand, over-extrusion and under-extrusion (explained in the section below), scars (nozzle grinding previously deposited layer) and stringing (unintended extrusion during what should have been a non-printing movement of the print head, resulting in thin strings).

How generalisable are the results from printing parameter studies?

The large number of articles and reviews on material-process-property relationships often report seemingly conflicting trends for the effect of printing parameters, although some main effects are clear (examples are given in reviews [49–53]).

One reason for the conflicting trends is that the studies use different slicer programmes, test specimens, materials and printers. Another reason is that there is interaction between the parameters, which many articles do not assess. Sometimes a change in one parameter setting changes the value of another parameter, which is assumed to be constant. If, for instance, the print head speed (Table 13.1) is set to a very high value, the temperature of the extrudate may decrease (due to limited heating capacity), and there may also be under-extrusion (lower actual volumetric flow rate than set in the slicer software). Also, at high printing speeds, there may be under-extrusion or over-extrusion due to accelerations and decelerations that the print head cannot deliver. This affects the extrudate profile/cross-section when starting and ending a certain extrudate strand and when changing direction, e.g., in a 90° turn.

In a systematic review, Golab et al. [25] questioned how generalisable the parameter optimisation studies are. The same concern was raised in a review by Popescu et al. [54]. Golab et al. [25] analysed 127 experimental polymer MEX studies on dimensional quality (including geometrical accuracy and resolution and surface finish) and evaluated which machines, materials, sample sizes, part geometries and printing and design/slicer parameters that had been used in the studies. They summarised that, in these studies, some printing parameters have been shown to have a significant effect on the printed parts and others less so. However, they concluded that a lack of agreement among the studies limits the generalisability of such studies for parameter optimisation. They argued for standardisation of part geometries and slicing software in such studies (more than half of the studies did not report which slicer software was used) and also a larger experimental sample size. Golab et al. [25] also noted that all the studies had considered macro-level errors, while these originate from errors at the scale of the extruded strands (sometimes referred to as the mesostructure). They pointed to recent studies that considered the local dimensional variance of the cross-section of deposited single strands and suggested more studies of this kind. This would contribute greatly to the understanding of the underlying causes of part defects and inaccuracy.

The same criticism regarding the generalisability of experimental studies can also be applied to studies of mechanical properties. Also in these studies, many seemingly conflicting trends have been reported.

What is the cause of the reported high anisotropy in tensile properties?

An interesting analysis of studies of mechanical properties was presented by Allum et al. [55,56]. They reviewed and analysed some of the literature and also performed new measurements with specially designed tensile specimens. Based on this, they claimed that reports of low tensile strength and strain at break in the direction perpendicular to the build platform (this strength is often referred to as "interlayer strength" or "Z strength") and resulting high anisotropy were not due to weak bonding between extrudate strands in adjacent layers (deficiencies of intermolecular diffusion and entanglement), but rather caused by two effects:

1 When calculating the stress, the true load-bearing cross-section of the test specimen was not used, leading to an erroneous, too low, stress value. The void content was not taken into account (in particular voids between extrudate strands), nor were grooves on the outside of the cross-section (callipers only measured the outer bounding box).
2 Grooves introduce strain concentrations that have a large effect on the measured strain at break (and toughness) of the "macro" specimen, i.e., the measured strain is not a material parameter due to the inhomogeneous strain along the gauge length.

Hence, Allum et al. [55] suggested that in many cases, the underlying cause of anisotropy and brittleness is geometric features at the scale of the deposited extrudate strands (grooves and voids between layers) rather than deficient bonding between strands/layers. (Deficient bonding is the main explanation given in the literature, often based on polymer physics theory for intermolecular diffusion and the formation of entanglements between polymer chains in adjacent deposited strands [49].) Based on their analysis of the literature and their own measurements, Allum et al. proposed that specimens attain bulk material strength for a range of printing conditions and materials. However, the researchers acknowledged that there could be cases when deposited strands do not have bulk-strength bonding. Many changes in printing or material parameters, e.g., increasing the nozzle temperature, could contribute to both better bonding and a reduction in voids.

Coogan and Kazmer [57] published data that led them to conclude that there are two factors that may cause low (apparent) interlayer strength (they used small tensile specimens laser cut from a box with single-strand walls): (1) insufficient pressure-driven interlayer contact (reducing the contact area between layers) and (2) lack of interlayer polymer diffusion (causing poor interlayer adhesion). This was based on experiments with a special instrumented 3D printer in combination with numerical modelling. A model for predicting interlayer contact based on pressure-driven flow was combined with a model for polymer chain diffusion to predict the interlayer strength. Interlayer contact was predicted based on in-line pressure measurements, while diffusion was predicted based on in-line temperature and viscosity measurements. The interlayer strength model was validated against strength measurements of parts made with high impact polystyrene, and this indicated that the strength of most parts suffered due to incomplete interlayer contact, while only some parts suffered from incomplete diffusion. The researchers concluded that they believed that lack of interlayer contact is the primary cause of low mechanical properties in most parts made by polymer MEX, and future work should focus on better understanding how layer geometry (road width and layer height) and pressure-driven contact affect interlayer strength.

Note that articles on polymer MEX and mechanical properties mostly use tensile testing, but other mechanical tests are also used, such as bending, compression, fatigue and fracture mechanics tests [54,58,59].

What is the best specimen for tensile tests?

Tensile tests are often used to compare materials and printers, as well as optimise printing parameters and monitor repeatability from build to build (e.g. using so-called "witness" specimens, i.e., test specimens printed together with the real parts). Printer and material manufacturers, such as Stratasys, have developed procedures [60] for the slicing (i.e. the layout of strands) and printing of test specimens with different orientations. The specimen geometries are often those of existing standards from ASTM, ISO, etc.

The question is how the specimen geometry, orientations, slicing parameters (e.g. raster angle, layer thickness and number of strands in contours) and printing parameters (e.g. nozzle temperature and print head speed) should be selected. Ideally, the set of specimens should provide a basis for a neutral comparison between materials and printers. It should also provide data that are representative of real parts made by MEX, as well as data that can be used in (finite element) structural analysis or other forms of analytical or numerical mechanical analyses.

Phillips et al. [61] reviewed current methods for preparing polymer MEX specimens for tensile testing (16 different specimen geometries were identified) and proposed guidelines for a new standard. The guidelines addressed the dimensions and fabrication of test specimens, build and raster orientation, slicing parameters, toolpath optimisation (for a given slicing), printer and material specifications and inspection of fabricated specimens. The review pointed out some main limitations of common test standards (such as ISO 527-2) when used for MEX specimens: (1) The standards do not address the fact that MEX specimens are influenced by unavoidable voids and gaps between layers and strands. (2) In the standards, the specimens are moulded or machined from plates, resulting in a relatively homogeneous structure from the bulk to the surface. On the other hand, for directly printed MEX specimens, the number of contour strands affects the mechanical properties, and in the case of no contours, the specimen will have numerous notches around the perimeter. There is also limited understanding of how machining a specimen from a printed part affects the results. (3) Specimen acceptance criteria based on visual inspection, as often prescribed in standards, cannot be applied directly to MEX specimens due to their mesoscale features, such as surface notches. Furthermore, as outlined in the sub-section "What is the cause of the reported high anisotropy in tensile properties?", measuring the actual load-bearing cross-sectional area of the specimen is not straightforward.

Sola et al. [62] also reviewed challenges and standardisation needs regarding tensile testing for polymer MEX. The review detailed the limitations of existing standards for polymer AM, such as strand- and layer-induced anisotropic behaviour and the complicated interplay between structural features at different length scales (micro/meso/macro), which undermine pre-existing concepts and theories regarding specimen geometries and size effects. They concluded that existing standards should be used with care. Furthermore, set-up and printing parameters should be fully reported, rectangular specimen geometries should be used rather than dogbone specimens (to avoid premature failure at the fillets), and the size of the specimens should not be changed arbitrarily.

Voids and other defects at the mesoscale

Unintentional voids (in particular between strands), gaps and grooves (on the outside of the parts), which are referred to as mesostructure or mesoscale defects, are recurring topics in the polymer MEX literature. The importance of such defects is in line with the mechanisms proposed by Allum et al. [55] and Coogan and Kazmer [57], as summarised in the sub-section "What is the cause of the reported high anisotropy in tensile properties?" above.

As a side note, voids and gaps also influence the part's permeability to fluids. This could be turned into an asset: Tao et al. [63] remarked that voids in printed parts form channels that could be utilised for heat and mass transfer. A related idea for introducing electrically conductive networks was recently published by Zheng et al. [64].

Some reviews address voids and their negative effects directly [63,65,66]. Sun et al. [65] reviewed how voids are formed and identified and how their occurrence can be reduced using three general strategies: void prevention, *in-situ* treatment, and post-processing. Pore formation can be slicer related directly by poor slicer algorithms that design problematic gaps or indirectly, e.g., by certain infill patterns that are more prone to producing gaps than others due to unavoidable under-extrusion for some of its mesostructure features. Sun et al. [65] classified and described different types of voids:

1 Voids between strands due to their non-tessellating shapes (the morphology of these voids depends, e.g., on the difference in raster angle (Table 13.1) between adjacent layers).
2 Voids resulting from gaps between strands in a given layer, due to (a) adverse slicer settings or deficient algorithms, (b) unintended under-extrusion (i.e. differing from the extrudate width in the G-code; see also Figure 13.2) or (c) unintended toolpaths (differing from the G-code). Note that the defects in (a) typically become more critical for complex geometries, e.g., geometries that are topology optimised and/or with lattice structures. Also, the defects may be more problematic for sparse infill than for

100% infill because local stress concentrations can be higher in the former case.

3 Voids inside strands, e.g., due to rapid solidification (causing vacuum voids), trapped gas or moisture in the filament.
4 Staircase defects due to the layerwise building and surface voids (due to local under-extrusion as in (2), but considered a separate category due to its effect on, e.g., surface finish).

The researchers [65] outlined several void prevention strategies, including toolpath optimisation (e.g. to minimise local under-extrusion) and parameter optimisation (e.g. optimising layer height and extrusion temperature). Voids can also be reduced by modifying the feedstock, e.g., by adding expandable microspheres that expand to fill voids in a post-processing heat treatment. *In-situ* application of, e.g., heating or ultrasonic vibration during printing can also reduce the void content. Post-processing using heat, ultrasound, lasers or chemicals can also reduce the void content or reduce the surface roughness. Tao et al. [63] published a good review with some of the same topics as Sun et al. [65].

Al-Maharma et al. [66] also reviewed voids and their influence on mechanical properties, addressing both MEX and PBF (metals and polymers). Regarding MEX of polymers with short fibres, they stated that pores inside the strands (affected by fibre-matrix adhesion) are the most critical. Regarding voids between strands, they mentioned that these could be reduced by optimising the exit geometry of the nozzle. The researchers also outlined how functionally graded material properties could be produced by polymer MEX and how functionally graded pores and unit cells could be used to tune strength and toughness. Wang et al. [67] reviewed composites with short fibres and stated that microvoids occurring near the fibres were critical factors for the mechanical performance. The microvoid formation was related to the local pressure distribution in the flow and also influenced by flow-induced fibre orientation, especially in thick extruded strands.

How to improve the mechanical properties and reduce the anisotropy?

Many reviews have addressed the challenge with the alleged weak interlayer bonding ("low Z strength") and resulting high anisotropy. This may not be due to poor bonding *per se* [55], as discussed in the sub-section "What is the cause of the reported high anisotropy in tensile properties?", but voids and other mesostructure defects certainly have an effect. For special materials, it has been demonstrated that void-free parts with isotropic tensile properties can be made [68].

As stated in the sub-section "Shortcomings of the process and typical part defects", issues such as voids, gaps and poor bonding may be inherent to the

MEX process, but several researchers have tried to address these issues to improve the mechanical properties via, e.g., material modifications, slicing algorithm improvements, printing process optimisation (which may be difficult to generalise [25] as summarised in the sub-section “How generalisable are the results from printing parameter studies?”), printing process modification, and post-processing.

Tran et al. [51] reviewed approaches for enhancing the tensile properties of printed parts based on the main hypothesis that the properties are limited by inferior bonding between deposited strands/layers. The review summarised the effects of printing parameters and focused on modification of materials, modification of printing processes, and post-treatment. The material modifications covered in the review included the following:

- Core-shell filaments
- Blends, e.g., polylactic acid (PLA)/polyamide-12 (PA12), with reactive compatibilisation and blends with thermo-reversible cross-links
- Low molecular weight surface segregating additives, e.g., comparison of 2-, 3- and 4-arm PLA star molecules in a PLA matrix
- Thermally conductive fillers (which, at medium loading, reduced pores and gaps)
- Fibres (which can have both positive and negative effects)

The reviewed process modifications included the following:

- Localised UV-induced bonding (with methacrylated PLA)
- Localised laser pre-deposition heating
- Nozzle-integrated pre- and post-heating
- Interface welding by dielectric barrier discharge (interfaces loaded with carbon nanotubes), pressing/vibration-assisted printing
- Printing in vacuum/inert atmosphere

Among the process modifications listed above, the heating methods gave large improvements and were relatively simple to implement. Finally, the researchers reviewed post-treatment methods such as ultrasonic welding, laser treatment (flattened the surface and closed internal voids), heat treatment (hot pressing and annealing) and microwave heating (using filaments coated, with e.g., carbon nanotubes).

Gao et al. [50] reviewed studies on improving the tensile properties in the Z direction, focusing on material modifications, with some overlap with the review by Tran et al. [51]. Gao et al. [50] made a distinction between chemical and physical material modifications (physical means blending with organic or inorganic additives or other polymers). The researchers stated that a reduction in the viscosity is favourable (via enhanced flow and interdiffusion), while organic bonding-enhancing additives need to have a certain molecular weight in order to make entanglements. The researchers also reviewed the mechanisms behind the weakness in the Z direction and noted that some changes in printing parameters that improved the Z strength gave a reduction in dimensional accuracy. The researchers listed published values for anisotropy in strength (based on specimens with different build orientations or with different raster angles; 0° vs. 90°). In some cases, the strength anisotropy was rather low (strength difference around 10%). However, the researchers did not list values for the anisotropy in strain at break (i.e. ductility), which was very large in some of these cases. This was typically for semi-crystalline polymers, for which the yield stress was reached for both orientations. (Also, many data sets were not corrected for the true load-bearing area [55].) The researchers reviewed some studies on process modifications and post-processing. Some process modifications involving heating by lasers or IR may negatively affect dimensional accuracy and surface quality, but it is claimed that the use of ultrasound does not have this negative side effect.

Material and printing process modifications for improving mechanical properties are also mentioned in some of the reviews cited in other subsections, e.g., Sun et al. [65], Al-Maharma et al. [66] and Vaes and Van Puyvelde [49].

Material-focused studies and challenges with semi-crystalline materials

The most common materials in the polymer MEX literature are PLA and acrylonitrile butadiene styrene (ABS) [25,54], although the leading printer manufacturer Stratasys has offered several other materials for many years, such as polycarbonate (PC), PC/ABS, acrylonitrile styrene acrylate (ASA), polyetherimide (PEI)/PC, PEI, polyphenylsulfone (PPSU) and PA12, including short fibre-reinforced grades. Today, a wide range of thermoplastics are available as filaments from a large number of suppliers, including major producers of plastics for high-volume processes such as injection moulding.

In addition to the reviews mentioned in the sub-section above, which summarise material modifications to improve Z strength, there are polymer MEX reviews focusing on specific materials such as ABS [69], polypropylene (PP) [49,70,71] and polyaryletherketones (PAEKs) [72] (the family that includes polyetheretherketone (PEEK)), thermoplastic elastomers [71,73,74], high-temperature engineering materials [20], semi-crystalline materials [49], specialities such as thermally conductive composites [75] and polymer MEX materials in general [76].

In addition to strength and anisotropy, dimensional accuracy and warpage are common topics in these reviews, in particular for semi-crystalline materials. These materials generally show large shrinkage upon solidification and have high thermal expansion coefficients, and the printed parts are therefore prone to internal stresses and warpage. These stresses can also cause delamination of layers as well as delamination from the build platform during printing. The extent of these problems depends on the part geometry and the mesostructure (the paths of deposited extrudates; strands). The printer also plays a role; a heated chamber with good temperature homogeneity is essential for some semi-crystalline materials [20].

Vaes and Van Puyvelde [49] published a comprehensive review of the literature on semi-crystalline thermoplastics for MEX, motivated by the need for more engineering and high-performance thermoplastics for demanding end-use parts. The researchers reviewed modifications of materials, e.g., blending and using additives to improve the properties of the printed parts, as well as printing process modifications. In addition to the well-known challenge with high warpage for these materials, the researchers also addressed phenomena that can occur during printing with these materials. One of these is insufficient melting and self-nucleation in the case of insufficient heat transfer and melting (when printing fast). The review discussed how the printing speed can be increased by modifying the nozzle design [77] or by pre-heating the filament with a laser [78].

Another phenomenon is flow-induced crystallisation which may occur at high shear rates (during extrusion) if the molecular weight is high enough [49]. Studies have shown that flow-induced microstructures can improve the mechanical performance of the printed part. Another topic discussed in the review [49] is the negative impact of crystallisation on chain mobility, which may affect the bonding between extruded strands. The reviewed literature included studies with interesting approaches for understanding the interplay between the heat transfer in the printing process and the crystallisation, such as combining infrared (IR) thermography data from the printing with crystallisation kinetics measurements using fast scanning chip calorimetry.

The crystal structure and the degree of crystallinity may depend on printing parameters and may vary through the printed part. There may also be time effects; the crystallinity may be different if several parts are printed simultaneously, leading to more time for cooling before a new layer is added. For a PP homopolymer, Wang et al. [79] observed that printed parts had a certain fraction of β phase in addition to the α phase (injection moulded parts only had the α phase), and the β fraction decreased with increasing extrusion temperature. Nogales et al. [80] reported that the degree of crystallinity in a PP part varied in the Z direction, through the top layer of the part, with a maximum at the centre of the layer, a minimum in the weld zone towards the layer underneath, and an even lower minimum at the top (free) surface. The crystallinity minima were explained by interfaces limiting spherulitic growth. They also observed that, in the top layer, the crystallinity was higher in a position close to a corner, and this was attributed to the lower printing speed in this position.

Improving part quality and repeatability by implementing monitoring and control systems

As for other manufacturing technologies, systems for process monitoring and closed-loop control are important for achieving good, repeatable and documented part quality. A natural extension of this is algorithms, e.g., based on machine learning, that can automatically calibrate and optimise printing parameters prior to printing a part, e.g., by printing several test strands with a new material. Such algorithms may also adjust printing parameters during printing based on prior printing sessions with the same material. During printing, such systems can act on random or systematic errors. The simplest action would be to stop the printing immediately to avoid wasting time and material.

The Measurement Science Roadmap for Polymer-Based Additive Manufacturing [81] presented four prioritised roadmap topics (RT) for *in situ* measurements:

- New *in-situ* imaging modalities
- Real-time process measurement at the required spatial and temporal resolution
- *In-situ* control and model integration
- Big data analytics

Oleff et al. [48] systematically reviewed a large number of publications on *in-situ* process monitoring of polymer MEX (221 publications, including 22 patents), demonstrating that the research activity in this field is high. Several sensor technologies and analysis algorithms were identified. The systems were categorised according to their functionality (increasing from categories 1 to 4):

1 Sensor systems as pure hardware setups
2 Systems based on (1), but data are processed and extracted, e.g., for visualisation
3 Automated data evaluation for detecting anomalies
4 Closed-loop control systems

For each category, the state of development was classified as either preliminary study, realised solution or patent. Most of the two former classes were in category 3 above. Most of the patents were in category 4. The systems were also categorised according to the element in the process that was monitored (feeding system, nozzle, build chamber, build platform or movement system, including motors) or the area of the part that was monitored (entire part, layers or sidewalls). Each of these categories was then broken down according to the type of sensor technology and analysis algorithms (e.g. variants of machine learning). The sensor technologies reviewed by Oleff et al. [48] are listed below (in order of decreasing use in the reviewed studies, except the "other" category). Note that different sensor technologies are often combined to achieve a more powerful monitoring system.

- **2D vision**: Typically camera systems, mostly for sequential inspection of layers but also sidewalls and entire parts. Fourier analysis of images of sidewalls can, e.g., be used to determine the variation in layer height. Seven of the 23 patents identified by the researchers exclusively addressed 2D vision.
- **Temperature**: Measuring and controlling the temperature of the nozzle, the build platform and the build chamber is standard for MEX printers. Many publications also use IR thermography, e.g., on layers or sidewalls.
- **Vibration**: Vibrations are, e.g., monitored for the extrusion head with an accelerometer. The data can be related to printing quality or nozzle clogging. Vibration monitoring can also detect part deformations and defects in mechanical components. Accelerometer data can be used to calibrate firmware parameters to reduce, e.g., ringing surface defects [82].
- **3D vision**: Structured light or stereoscopic imaging systems are, e.g., used to monitor individual layers. Laser triangulation systems attached to the extrusion head can record single-height profiles, which are combined into 3D images.
- **Acoustic emission (AE)**: Various anomalies can be detected by AE monitoring, e.g., for the print head and the movement system. Detachment of the part from the build platform and deformations can also be detected. Furthermore, AE monitoring can be used to identify cyberattacks (e.g. trying to weaken the part by modifying the infill structure, which is hidden in the final part), by comparing it with the original AE "fingerprint" or even the G-code.
- **Electrical signals**: The currents of the motors pushing the filament through the extrusion head or moving the axes can be measured. Nozzle blockages or incorrect axis movements can be identified. The extruder motor current is correlated with the nozzle pressure, which again can be related to part strength [57] and various defects.
- **Force and pressure**: There are, e.g., patents on measuring the contact force against the nozzle and the pressure in the nozzle.
- **Other**: Many other sensor technologies have been explored or demonstrated, but each with a small share in the literature reviewed by Oleff et al. [48]. Some examples are fibre Bragg grating sensors (embedded in parts during printing, for monitoring strains, e.g., due to warpage), ultrasonic sensors (to analyse part structure) and encoders (for closed-loop control of axis movements or filament feeding rate).

Another excellent review of polymer MEX process monitoring was published by Fu et al. [83], who presented more details and examples for the various methodologies than Oleff et al. [48]. A few recent non-review articles can also be mentioned, typically using instrumented printers to study the fundamentals of the processes, including limiting factors, error sources and process stability.

As summarised in the sub-section “What is the cause of the reported high anisotropy in tensile properties?”, Coogan and Kazmer [57] claimed that lack of interlayer contact during printing is the primary cause for low mechanical properties in most parts. They demonstrated real-time strength monitoring based on data from a filament encoder (to verify the flow rate) and measurements of melt pressure and temperature in the nozzle. Colon et al. [84] also used a print head with several sensors and studied rheological and thermal transients. They showed that the pressure and flow are sensitive to the extruder configuration and that a melt pressure sensor provides the clearest estimation of the rheological state in the nozzle. They advised that care should be taken in selecting and mounting extruder drive gears to minimise low and high frequency fluctuations due to gear eccentricity and teeth-to-filament engagement, respectively. In another study, Colon et al. [85] used an instrumented setup to study the swelling of the extrudate as it exits the nozzle. The swelling affects the dimensions of the extruded strand and may induce residual stresses. The study reported the effects of volumetric flow rate, nozzle temperature and nozzle orifice diameter on swelling and also compared this to numerical simulations.

Filament slippage and filament diameter in the extruder were measured by Greeff and Schilling [86] using a low-cost camera and image processing, allowing for real-time volumetric flow rate estimation. The amount of slippage varied with nozzle temperature and feed rate and therefore could not be fully corrected for. A proof-of-concept closed-loop control reduced the amount of slippage.

Fischer et al. [87] demonstrated in-line measurement of the extrusion force on the nozzle in a test rig. They used a compact and concentric setup, which allowed an accurate measurement, avoiding parasitic effects. Measuring the effective extrusion force on the nozzle allows for the characterisation of the flow behaviour of the molten polymer. The gap between the filament and the cylinder (at the entrance to the nozzle) can cause a backflow of the melt. This affects the heat transfer, especially at high feeding speeds. This gives a transition from stable to unstable extrusion (above a certain speed, the backflow causes oscillations), and this transition can be determined by extrusion force measurements.

Finally, several researchers have studied the temperature field in the nozzle [77, 88] and also the temperature development all the way to the printed part [89], with a combination of experiments and simulations, thereby identifying routes for further development of hardware and process control.

Scalability (part size and productivity) in an industrial context

Compared to geometries commonly used in scientific studies, real industrial parts may be smaller or larger, and they can have higher geometrical complexity at various length scales. There are geometrical scale effects that must be taken into account when designing parts for MEX, but few articles address this specifically. Grubbs et al. [90] noted that MEX "has seen limited scalability in functional part production partly due to the difficulty of process optimisation with its complex parameter space, including material type, filament characteristics, printer conditions, and slicer software settings". In an industrial context, scalability could be related to part size (or printing several parts at once) and geometrical complexity, but also scalability in terms of changing to a different filament/material or transferring the production to a different printer, offering better productivity or quality.

Many scientific studies (summarised in the sections above) focus on defects at the strand scale, and most of these defects are present for large and small parts alike, although some defects may depend on the geometrical complexity. Scientific studies typically use rather simple test geometries in order to reduce the number of defect types and make the interpretation of the results easier. Regarding geometrical scale effects, the sub-section "How generalisable are the results from printing parameter studies?" mentions studies reporting effects of, e.g., layer thickness and contour thickness (number of strands), as well as results for different part geometries/sizes. However, as mentioned in the same section, these published results can often not be generalised to other part geometries or printers.

Some publications have addressed upscaling to larger printing areas and volumes. Owens et al. [91] presented a heat transfer modelling approach, which they claimed to be applicable from small desktop MEX printers to big area MEX printers. Intralayer temperature gradients in the printed part were highest for the largest scale. According to the researchers, the model can be used to explore the influence of layer geometry, layer time, and bed temperature on the temperature distribution in the printed part. Riggins and Dadum [92] pointed out that one obstacle to MEX scalability is residual stresses in the printed part, arising due to the complex thermal history of molten polymer deposition and solidification. Shah et al. [23] considered challenges when upsizing MEX printers (e.g. horizontal build area above 0.5 m × 0.5 m), such as frame designs and kinematic designs, large diameter nozzles, control of the environment temperature, and overall printing time. Vieira da Silva et al. [93] presented a parametric calibration study of MEX with a large nozzle diameter (1 mm). With upscaling as motivation, they noted that the reduction in printing time with a larger diameter is accompanied by reduced printing resolution and reduced control of the rheological behaviour, leading to poorer surface finish and geometrical tolerances. Zhang et al. [89] presented a systematic analysis of the temperature development, from the filament entering the extruder to the printed part. An interlayer time similarity rule was formulated for printing single-walled structures, which states that the temperature fields are comparable for processes sharing the same interlayer time. Based on this, the researchers claimed that knowledge obtained from printing small objects can be transferred to large objects.

One approach to reduce the printing time, in particular for large parts, is to use several print heads, printing in parallel. With this approach, the nozzle diameter can be kept small, thereby maintaining high resolution and avoiding some scaling issues. However, controlling multiple print heads is not straightforward, and this is an active research field [94–96].

The slicing software is a key element when it comes to optimising printing time vs. surface quality and mechanical properties. Slicing software often has different settings to choose from a given nozzle diameter, e.g., settings optimised for short printing time, good surface quality or good mechanical integrity, as well as well-balanced compromises. A slicing feature that can reduce the printing time while maintaining good surface quality is to slice the part with a variable layer thickness, depending on the angle between the platform and the part surface. As a variant of this, an anti-aliasing technique that provides sub-layer accuracy has been proposed [97]. Another slicer feature is based on variable strand width [65, 98], which can reduce mesoscale gaps for a given nozzle diameter, both by providing thinner/thicker strands locally and by reducing local under-extrusion. Yet another technique, more complicated than the ones above, is to slice for non-planar printing [99,100]. This technique can be used to improve surface finish and mechanical properties, and it can also eliminate the need for support structures.

The firmware of the printer can also have an important role in enabling faster printing, at least for some materials. Open-source firmware packages such as Klipper [101] and Marlin [102] have contributed to the development. One such firmware module [82] reduces ringing defects by reducing resonance vibrations based on analysis of the printer movements, e.g., using an accelerometer mounted on the print head. Another firmware module [103] reduces the problem that the print head fails to deliver the correct extrusion rate when the print head accelerates and deaccelerates, e.g., in a corner. Hence, this module aims to reduce temporal under-extrusion or over-extrusion relative to the extrusion rate set in the G-code. The parameters of this firmware module can be calibrated for a given nozzle and filament/material by printing a certain test structure. Tronvoll et al. [104] discussed an algorithm used in such a module and its performance.

Summary and industrial perspective for MEX technologies

The MEX process builds a part with strands as the building blocks in a mesostructure. This offers great geometrical freedom, but the mesostructure is prone to defects such as gaps and voids and poor bonding between strands and layers.

In this review, we have focused on basic defect mechanisms and how these affect part properties, in particular mechanical properties. Furthermore, we have summarised how part properties and processability can be improved by developments in polymer materials, hardware, firmware and software. Some literature critically assessing methodology and interpretations has also been summarised (in the sub-sections “How generalisable are the results from printing parameter studies?”, “What is the cause of the reported high anisotropy in tensile properties?” and “What is the best specimen for tensile tests?”).

Via the mesostructure, the properties of a printed part and the printing speed are partly limited by the physical properties of the polymer material and partly by the printer hardware, via both steady-state and transient effects, and instabilities. Key polymer properties include rheology, polymer chain mobility (intermolecular diffusion and entanglement), solidification kinetics and shrinkage. The printer hardware affects aspects such as the capacity for delivering a molten strand with homogeneous temperature, and it affects printer resonance vibrations. Polymer properties and hardware together affect limiting factors such as the under-extrusion and over-extrusion during acceleration and deacceleration of the print head.

The slicer software is important, and assuming ideal materials and printers, the sliced geometry can be optimised for printing speed, mechanical properties or surface finish, and good compromises can also be obtained. A good slicing algorithm should also take into account defects occurring with real materials and printers and adjust the mesostructure to be printed accordingly.

Monitoring and control systems, including firmware, have improved the reliability and repeatability of the MEX printers, thereby improving the printed parts’ structural integrity, geometrical tolerances and surface finish. These systems also provide documentation of the manufacturing process and part quality. Automation systems are also available, e.g., for integration with post-processing.

Developments in hardware, software and firmware have been led by printer manufacturers (where it all started more than 30 years ago), the scientific community (the basis of most of this review), the open source community (with important contributions to all aspects) and material manufacturers (tailoring materials for processability and end-use properties). Note that AM is a digital and physical process chain, not “just a machine”.

Many polymer MEX technologies are mature, but there is a steady flow of improvements and innovations aimed at improving productivity and part performance. There are now many types of polymer MEX printers for industrial use. There are “all round” printers and printers tailored for specific uses, e.g., medical (with “clean” chambers), high-speed (e.g. with special kinematic designs) and high-temperature engineering plastics (with heated chambers, integrated annealing, etc.). Many technologies with good "value for money" are now available.

Powder bed fusion (PBF)

Processes, machines and materials

Polymer parts can also be additively manufactured using polymer powders as a feedstock. The main methods of PBF will be described here, two of which – PBF-LB (PBF with laser beam) and Multi Jet Fusion (MJF) – are shown in Figures 13.4 and 13.5, respectively. PBF uses the concept of an energy source to fuse specific particles together to make a solid mass supported in a bed of unfused particles. In the case of PBF processes for polymers, the process is applied to thermoplastic polymers, and the focused energy source is usually a CO_2 laser beam (PBF-LB). The path of the laser defines the area of polymer particles that are fused together in the build plane. Three-dimensional parts are created by covering this new solid layer

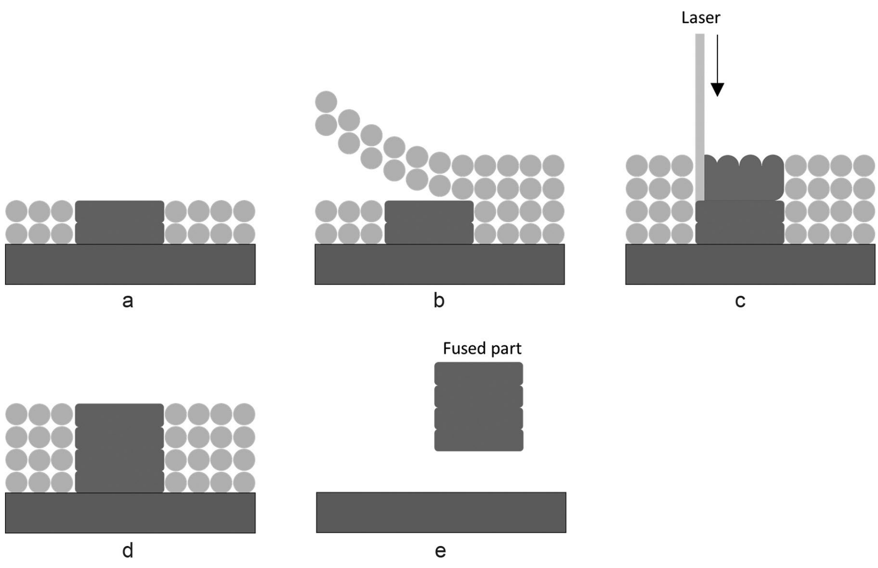

Figure 13.4 Illustration of powder bed fusion (PBF) by laser beam (PBF-LB): (a) a structure is built layer by layer in a powder bed on a substrate; (b) a powder layer is deposited on top of the previous fused layer; (c) the surface powder is locally heated by a laser to form a local polymer melt pool; (d) the melt cools into a new solid layer. This process is repeated to build layer by layer until the part is complete; (e) the loose powder is removed and the fused part is removed. (Adapted from [111], with permission from Elsevier.)

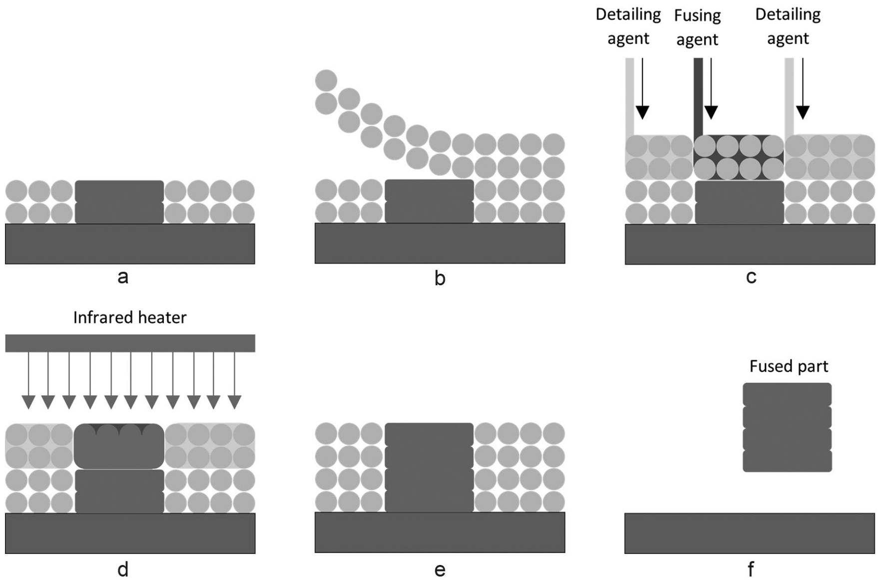

Figure 13.5 Illustration of multi Jet fusion (MJF): (a) a structure is built layer by layer in a powder bed on a substrate; (b) a powder layer is deposited on top of the fused previous layer; (c) fusing ink and detailing agent are locally deposited to define the geometry of the new layer; (d) the surface powder is non-locally heated to locally fuse where the fusing ink has been deposited; (e) the melt cools into a new solid layer. This process is repeated to build layer by layer until the part is complete; (f) the loose powder is removed and fused part is removed. (Adapted from [111], with permission from Elsevier.)

with a thin layer of polymer particles, which are then fused to the previous layer and to each other. The layer thickness is typically in the range of 60–180 micrometres, depending on the powder particle size and the desired geometrical resolution and printing time. By moving the build plane away from the laser source by a distance equivalent to the layer thickness, the build plane is always at a constant distance from the laser source. This process is repeated layer by layer to build a three dimensional part. A review of the various aspects of the process is covered in some depth by Lupone et al. [105].

High-speed sintering (HSS) [106–108] is an AM method that also creates parts layer by layer from a polymer powder. Unlike PBF-LB, which uses a focused laser beam to fuse the powder particles in the path of the beam, HSS instead uses a print head that selectively deposits liquid ink onto a powder surface in the areas that will be subsequently fused, similar to how a print head passes over a paper surface in conventional 2D inkjet printing. On the application of IR radiation, the areas coated by the IR-absorbing ink reach the temperatures required to fuse the particles into a solid mass, whereas the uncoated powder particles do not.

MJF is an AM method developed by HP that has some similarities to HSS and creates parts layer by layer using powder as feedstock [109–111]. A print head travels over the surface of the polymer powder in a build plane and deposits liquid inks: a fusing agent and a detailing agent. The print head also contains an IR light source, which exposes the local powder surface to non-focused thermal energy. The areas of the polymer powder surface that have been coated in the fusing agent absorb a greater amount of thermal energy (in some cases due to the inclusion of graphitic carbon to increase IR absorption [112]), enabling the fusing of these particles when exposed to IR heating from the print head. The areas of the polymer powder surface that have been coated with the detailing agent are able to absorb more thermal energy without being fused together and therefore help to define the edges of the fused area [113]. In some areas of the build plane, these two liquids can also be applied together to control the heat generation in the fused areas [114].

MJF also allows for full-colour prints with colour controlled at the voxel level due to the ink-based processing. With eight inks/agents, full CMYK colours can be achieved, as well as black and white. Such printers were introduced by HP in 2018. With this principle, ultraviolet-sensitive and conductive materials have also been demonstrated.

The majority of polymers that are used in PBF processes are semicrystalline thermoplastics. The most common polymers in commercial PBF are PA12, polyamide-11 (PA11) and thermoplastic polyurethanes (TPUs). Other polymers used commercially include polyamide-6 (PA6), PP and PAEKs. Polyphenylene sulphide (PPS), polyoxymethylene (POM), polyethylene terephthalate (PET), and polycaprolactone (PCL) are also possible. Amorphous thermoplastics such as ABS, polystyrene (PS), PC and polymethylmethacrylate (PMMA) may also be used [115–117]. In addition, thermosetting polymers available as powders may also be used. These undergo curing initiated by a laser source in a PBF process [118].

The powders may contain fillers such as metal or glass particles or short fibres to enhance the properties of the parts [119–121]. There are several studies of polymer PBF with added glass or carbon fibres, and these report a preferred fibre orientation in the powder spreading direction, i.e., the direction the powder recoater unit is travelling [122–124]. The degree of orientation depends on the type of recoater (roller, blade), the recoater speed and the layer thickness. The orientation mechanism is the shear flow induced by the recoater. Numerical models have been used to understand the flow dynamics in the recoating/packing process and also the formation of voids [125]. In many cases, the fibre orientation is low.

PBF processes are in constant evolution, and a review of published literature on PBF processes with polymer materials from Web of Science shows an increase in the scientific publishing in this field, see Figure 13.6. The number of publications identified for PBF processes in this particular search shows

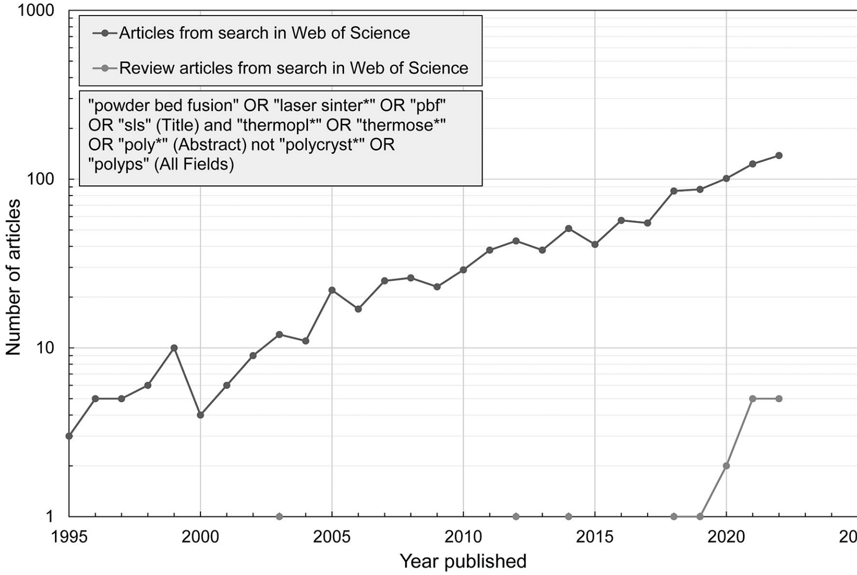

Figure 13.6 Results of a literature search for articles about polymer PBF in the Web of Science in February 2023. The search expression is given in the grey box. A large number of publications on PBF for metallic powders have been published, although most of these have been excluded from the search by the inclusion of thermoplas* and thermose* search criteria in the abstract. In some cases, PBF, including polymer binders to fuse metallic and ceramic particles, is included in these literature search results.

an increase over time, but without the recent large increase seen for MEX in Figure 13.3. One reason for this is that, compared to MEX, PBF printers are more expensive and often not used with third-party materials, and fewer PBF printers are built and modified by research groups.

Properties of PBF parts

The industrial application of PBF depends on the quality of parts produced by these methods (compared to conventional manufacturing methods [126]), as well as other factors such as economical and sustainability drivers. The properties of polymer parts produced by PBF processes depend on a number of factors, including the choice of polymer feedstock (which sets the limits on what is achievable from the AM part) and the processing parameters (for example, irradiation times and temperatures, bed temperature, powder dispersion methods and build orientation), which together control properties such as porosity, degree of particle melting, morphology of the polymers, the mechanical properties of the parts and their dimensional accuracy).

Varying degrees of anisotropy are reported for parts produced by PBF [111,127–130]. The mechanical anisotropy is typically largest for the tensile strain at break (ε_B). As an example, for PA12 in PBF-LB, Cai et al. [111] reported that the ε_B values were almost isotropic around 27–28% in the *xy* plane, but only 15% in the *z* direction. For a different PA12 in MJF, the same article reported ε_B values of 27%, 16% and 15% in the *x*, *y* and *z* directions, respectively. Regarding tensile strength, the PBF-LB process gave almost the same values (44.0 MPa) in the *xy* plane and a slightly lower value in the *z* direction (39.6 MPa). However, the MJF process gave the high value in the *z* direction (49.6 MPa) and 48.7 MPa and 44.5 MPa in the *x* and *y* directions, respectively.

Another issue with PBF is that mechanical properties and anisotropy can vary with the position in the build chamber due to inhomogeneous temperature. All in all, anisotropy and in-build variations have been reduced in recent years by improvements in machines and materials.

There are also some variations reported to be due to the various test methods [107], although the effects of different processing parameters necessitated by the different processing routes mean that different processes can be difficult to compare fairly. Craft et al. [131] reported the effect of fusing time on the mechanical properties of test parts, comparing PBF-LB, MJF and a third, in-house-developed PBF process called Large Area Projection Sintering (LAPS), which uses a planar light projector to heat a larger area while simultaneously enabling longer heating durations and reduced thermal gradients. As well as time optimisation, thermal optimisation also plays a part to enhance part quality and reduce energy consumption. For example, Schlicht et al. [132] recently reported on non-isothermal heating by using fractal exposure paths to better control the fusion temperatures in PBF of semicrystalline polymers and reduce the overall energy consumption of the process. Another example is given by Antończak et al. [133], who describe the use of multiple lasers: one to preheat powder local to the fusing area and a second laser to fuse the particles to define the part.

With PBF processes, it is difficult to avoid porosity in the finished parts [120,134,135], which leads to structural weakness in parts and, in some applications, allows fluid ingress. The pore size distribution and pore morphology are key factors for the mechanical properties. Inline optical methods to measure porosity during PBF processes have been proposed to enable quality control during manufacturing [136].

Factors affecting the industrial implementation of PBF

To implement a PBF process as an industrial AM route, the output rate of parts needs to be acceptable in relation to the required production volume, and the cost per part must be acceptable. For processes such as MJF, the cost per part has been compared with injection moulding (which needs a mould), and for a given part geometry, the break-even point can be in the range from 100 to above 10,000 parts [137,138]. Geometrical complexity and small part size favour PBF vs. injection moulding, and PBF offers a shorter lead time. Furthermore, the software for preparing the PBF print job has algorithms for effective filling of the build volume with similar or dissimilar parts, and also nesting parts.

The output of a single AM machine is dependent on the number of parts simultaneously produced per build volume and the cycle time of the additive process. For the PBF process, Lupone et al. [105] described various temporal regimes; the longest of these is the solidification/crystallisation regimes, which last on the time scales of minutes, whereas dispersing the powder is of the order of seconds, and irradiation and thermal diffusion processes are less than seconds. These regimes are not necessarily exclusively sequential in the additive process; the solidification/crystallisation of previously built layers may be ongoing while new layers are being processed on the build plane. The optimisation of these regimes within the additive process may be aided by inline monitoring, for example, by using laser profilometry to continuously measure layer powder density and part distortion [139]. In addition to this additive process time, the total time to manufacture a part using a PBF process also includes preparation for additive processing (for example, filling and preheating the powder bed) before processing, removal of AM parts from the powder bed, and post-processing steps such as smoothening or colouring parts. As of 2022, the production rates of MJF and HSS are reported to be several thousand cubic centimetres per hour [107].

Various researchers have reviewed the range of post-processing steps for AM polymer parts by mechanical, chemical and thermal processes [140,141]. Often, post-processing is performed to reduce surface roughness (e.g. due to the powder particles for PBF) and smoothen the appearance of steps associated with build layers. In the case of PBF parts, mechanical post-processing is also used to remove loosely bound particles on the build surface, for example, by glass bead blasting [141]. Mechanical post-processing includes sand/glass bead blasting and machining. Some chemical surface treatments rely on the selection of liquid chemicals to locally soften the surface material and smoothen the extremities. The selection of chemicals, either for dipping or vapour exposure, is thus determined by the polymer to be smoothened, and it may be performed at elevated temperature, as necessary. Other chemical treatments are additive; additional material may be coated or plated onto the surface to cover a rough AM surface with a smoother one. These new surfaces also enable AM parts to have improved surface functionality or chemical or wear resistance. Thermal treatments of AM parts may include targeted surface heating by IR heating or hot air jets, or non-localised heating by annealing in air or by hot isostatic pressing to reduce internal porosity [135]. The effect of thermal annealing on the mechanical performance of different lattice structures produced by MJF was reported to result in increased compressive strengths in some lattice designs [142]. Mechanical treatments are most readily performed on flat external surfaces, whereas chemical or thermal treatments may also be applied to the internal surfaces of complex parts. Of course, different surface treatments may be combined; for example, heating may be applied during mechanical abrasion to soften the surface during polishing. In addition, post-processing processes that are subtractive (such as mechanical polishing) or additive (such as coating) will affect the accuracy of the part geometry.

To minimise manufacturing costs, it is usually advantageous to minimise the number of processing steps. Any post-processing required will add to manufacturing costs and production time. Many of these post-processing steps are typically manual activities. Horstkotte et al. [143] recently investigated the automation of post-processing following PBF manufacturing as part of a potential industrial implementation.

A further limit for the industrial application of PBF processes is related to the build volume available in a piece of AM equipment. While it may be advantageous to fit as many parts as possible into a build volume, this may mean printing similar parts in different orientations relative to the build direction. Any part anisotropy may then lead to part-to-part variations in properties and surface features within a single production run. Zhang et al. [144] reported the development of algorithms to maximise available build volumes while considering the effects of build direction on part properties. Mele et al. [145] reported on direction optimisation in PBF processes as a contributor to packing optimisation, using algorithms to replicate the decision-making process of a human expert. The combination of such algorithms can therefore be implemented simultaneously with part design to optimise the available build volume and thus increase part output with the available equipment. The properties of parts produced using MJF are reported to be relatively uniform when manufactured in different positions within a build volume, with some variations of porosity and surface roughness [146].

Multimaterial components produced using PBF

As mentioned earlier, several polymer powders are available containing fillers; these can be used to create short fibre-reinforced composite parts without significant variation across a part. For some parts, it is advantageous to have variation in properties within a single part, which may be achieved by varying the powder materials in a single PBF build. Multimaterial AM processes have, e.g., been reported for metal PBF and for polymer PBF and MEX, as reviewed recently [147–149]. However, most conventional polymer PBF processes use single materials, as the parts are fused from a bed of a single type of powder. In principle, it is possible to vary the powder used in a layerwise approach, but this limits material variations to planes in the z-direction and is likely to be challenging to implement in industrial practice. A more feasible approach to create multimaterial parts in PBF may be by controlling powder deposition spatially in the build plane before laser irradiation, although this also

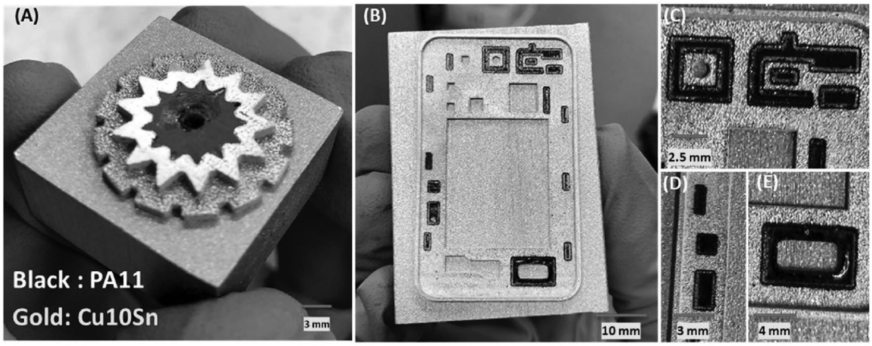

Figure 13.7 Multimaterial metal (copper alloy) and polymer (polyamide 11) parts made using a PBF process. (Figure reproduced from **[151]** with permission from Elsevier.)

limits material variation in the build plane. Stichel et al. [150] demonstrated an approach to combine different polymer materials in the build plane, by having multiple powder deposition heads. This enabled parts comprising, for example, hard and rubbery thermoplastics in a single part. Chueh et al. [151] demonstrated a proprietary multimaterial PBF machine to deposit metal and polymer powders in the same plane again by controlling the spatial dispensing of polymer and metal powders, followed by controlled laser irradiation. Examples presented by Chueh et al. are shown in Figure 13.7. The temperature required to fuse most metal powders is much greater than the temperature required to fuse polymer powders, so there is a risk of polymer degradation close to the polymer-metal interface in polymer-metal PBF processes.

The load transfer between different materials in a multimaterial part depends on the quality of the interface between the materials. This in turn depends on the chemical compatibility, but the design flexibility of AM enables mechanical features to be integrated into the interface design to add mechanical interlocking features and increase contact areas to increase the effective interface strength. While combining materials may have benefits for the performance of the products and enable new designs, the combinations may also complicate end-of-life management of the parts if the different materials have different recycling processes necessitating material separation.

Other industrially relevant polymer AM process categories: Vat photopolymerisation (VPP) and material jetting (MJT)

Vat photopolymerisation (VPP)

An important AM process category for polymeric materials is VPP [1]. A main difference between VPP and the two process categories reviewed above is that VPP uses thermoset materials (a "resin", which is polymerised and chemically crosslinked from a resin vat by UV/light) rather than thermoplastics. Recently, thermoplastic materials for VPP have been reported in the literature, but achieving polymerisation of thermoplastics on a timescale acceptable for AM processes is challenging [152,153]. However, there are now many thermoset VPP materials that can be used for manufacturing industrial parts with very good and almost isotropic mechanical properties, high thermal resistance, etc. There are also some VPP processes that are aimed at making such demanding parts, e.g. printer technologies from Carbon and Fortify. Polymer parts manufactured using VPP processes have reached the market recently in products such as the midsoles of running shoes [154].

The advantages of VPP include high geometrical resolution, a good surface finish, nearly isotropic material properties (for many resins) and fast printing (especially for printers with "2D illumination" of the vat via DLP or LCD technologies instead of lasers). A drawback of VPP is that the thermoset materials cannot be mechanically recycled. Furthermore, handling some of the resins and cleaning the printed parts require special HSE requirements. Also, post-curing of printed parts is nearly always needed, but still, the total production time per part can be low compared to other polymer AM processes.

Material Jetting (MJT)

As with VPP, MJT [1] typically uses photopolymerisable materials. In MJT with such materials, droplets of resin are deposited in the desired position on a build platform using technology analogous to the deposition of ink droplets on paper in conventional inkjet printers. The deposited resin is then cured by UV light to build a layer, and the process is repeated layer by layer to build three-dimensional structures. However, due to material costs and material properties, MJT is less industrially relevant than the other AM processes considered in this review.

MJT with thermoplastics has been embodied as the *Arburg Plastic Freeforming (APF) Process* as presented by Gaub [155] and Hentschel et al. [156–158]. In this process, thermoplastic melts are created directly from a melt extruder and ejected using a piezoelectric valve in a stream of droplets onto a moving build platform. As with the other melt deposition processes, three-dimensional structures are then built up, layer by layer. The need for a melt extruder necessitates a significant equipment investment. Since the stream of droplets is molten thermoplastic, the temperature control of the build chamber is of paramount importance to control the cohesion of the deposited droplets with the previous layer. As for all melt processes with semicrystalline thermoplastics, the cooling rate will also affect the crystallinity, dimensional shrinkage and final mechanical properties of the printed part [157].

MJT has been reported with a range of amorphous thermoplastics such as ABS [159], PC [160] and PMMA [157], with semicrystalline thermoplastics such as PP copolymers [158], PLA [161], PA6 [162] and thermoplastic elastomers [163], including TPUs [164,165]. Minetola et al. [166] compared the accuracy and resolution achieved with thermoplastic MJT with representative MEX and PBF processes, although using different polymers. As with other deposition processes, printing parameters such as layer thickness and discharge rate affect the total build time and part porosity [167].

Sustainability

Sustainability is an important aspect of the industrial implementation of AM. The implementation of AM to enable local, on demand manufacturing, the reduced need for tooling and the reduction in part inventory will impact the carbon footprint of manufacturing when compared to conventional manufacturing routes to make polymer products, such as injection moulding. In addition, redesigning parts to take advantage of the design freedoms enabled by AM may reduce material consumption and reduce part mass, reducing the environmental impact associated with raw material production and part transportation.

Metal AM is often compared to metal machining, and then metal AM has the advantage of less waste (although the machining waste is of course recycled). For polymer AM, injection moulding is often the reference process, and in this case, polymer AM does not have such an advantage. For injection moulding, production scrap, such as cold runners, is easily recycled by the machine, while this is not so easy for polymer AM. For polymer MEX, scrap can be converted into new filaments, but this requires energy. Also, MEX requires support structures for some parts, which increases material consumption.

For PBF, the polymer particles in the powder bed are held for extended periods at elevated temperatures, so that the fusing energy source (a laser beam) only needs to raise the temperature slightly to achieve fusing. The storage of the polymer powder at elevated temperatures may result in chemical degradation of the polymer powder, which could reduce the mechanical properties of PBF-manufactured parts [114,129,168,169]. In a single print process, depending on the size and geometry of the printed part relative to the powder bed, only a small proportion of the polymer powder may be used in part manufacture, while the remaining powder will be used for subsequent print jobs. Therefore, some parts of the polymer powder may have been held for cumulatively long periods at elevated temperature before being used in a part. New materials/powders have been developed in recent years, with better stability in terms of maintaining their properties (processability and end-part properties) through many build cycles.

The flexibility to produce spare (sometimes obsolete) parts on demand contributes to extending the life of products and systems. This contributes to reduced climate and environmental footprints, in addition to possible reductions in lead time and cost compared to conventional manufacturing. An example of this is to replace a broken fan on an otherwise functional and expensive pump. As with any manufacturing process, reducing waste and managing recycling of waste materials generated during AM processes are important, as are optimising machines and processes to minimise the consumption of electrical power [170].

Regarding the materials used, Chyr and DiSimone [171] recently reviewed the development of more sustainable polymers for AM. They pointed at two aspects of the development: (1) greener reagents and feedstock, including feedstock from renewable resources and (2) intentional design of materials for reprocessing (recycling) or degradation. Garcia et al. [172] used life cycle assessment to determine the global warming potential (GWP) of an example part made from ABS polymer using either conventional manufacturing (injection moulding) or AM (MEX). The researchers reported that the GWPs of the two routes depend on the production volume; a lower environmental impact is estimated from AM when the production volume is low, while higher volumes favour injection moulding.

Weise et al. [173] compared the energy and resource use for PBF-LB and MJF automotive components. In their case study, the MJF process itself was reported to be less energy efficient but had higher powder reusability than the PBF-LB process. Thus, the total energy and resource use depend on both the AM process and the material feedstock. While most polymer materials for AM are derived from petroleum, the sustainability of a range of biobased polymers for MEX and VPP has been reported by Sanchez-Rexach et al. [174] and Chin et al. [153]. Recently, polymer powders with an almost 50% reduction in carbon footprint have been reported for use in PBF processes [175]. Mele et al. presented a life cycle assessment (LCA) of the APF MJT process [176]. The production of the machine and its energy consumption were the most influential factors. Due to different building times, a fossil-based material (ABS) scored better in the LCA than a bio-based material (PLA).

In addition to climate and environmental aspects of AM processes with polymers, some health risks associated with inhalation of fine powders (from PBF processes) and volatiles from melts (from PBF, MEX or thermoplastic MJT processes) or resins (from VPP processes) need to be taken into account when assessing the implementation of AM processes [177,178].

Conclusions

A review of recently published literature confirms increasing academic interest in the development of materials, hardware, firmware and software for AM with polymer-based materials. The industrial implementation of these technologies is implicit in these publications and marketing materials published by suppliers of AM equipment and materials.

As described in this chapter, further increases in the uptake of AM for polymer parts are dependent on technical factors related to the AM processes and materials, such as achieving high-quality parts and reducing manufacturing time, and commercial factors such as reducing costs for smaller production volumes (e.g. by removing the need for expensive tooling) or reducing the time to market. Different market segments and geographical areas also show variations in the industrial implementation of AM for polymer parts.

The AM processes for polymers that are considered to be most industrially applicable for the manufacturing of products are summarised in this chapter: MEX, PBF and VPP. There are several variations of technologies within each of these categories, and each has its own strengths and weaknesses. Advancements in AM technologies (for example, to improve part resolution, reduce the surface roughness and anisotropy of parts, or reduce manufacturing times and energy consumption), together with increases in available polymer materials (for example, to improve part performance, reduce carbon footprint or enhance recyclability), are all expected to contribute to increased industry uptake of these polymer AM processes. Multimaterial AM can lead to more complex parts and functionally graded material properties, although the combination of materials in discrete parts should be balanced against the need for material separation for recycling at the end of life if the materials that are combined in AM processes have different recycling requirements.

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Chapter 14

On the degradation and lifetime prediction of filament wound composites subjected to thermal environmental sub-Tg aging

Chaman Srivastava and Sotirios Grammatikos

Introduction

Glass fiber-vinylester reinforced-filament wound composites (FWC-GFRP) are commonly used in applications that involve harsh service environments due to their increased corrosion resistance [1, 2] as compared to epoxy and bio-based polymers [3]. The evaluation of the response to thermal aging at different temperatures below the glass transition temperature (sub-Tg) can facilitate the design process of composite structures for dry and low humid service environments. Filament winding is a commonly used processing method for producing tubular structures in large volumes. Filament wound structures have high complexity [4] and anisotropy [2], are comprised of fiber, resin, and manufacturing-induced voids [5, 6], and are characterized by a high strength-to-density ratio [7]. The most common applications of filament winding are for manufacturing long and slender structures like pipes used commonly in oil, gas, and marine applications. Operational conditioning during service may lead to physical and chemical changes, negatively affecting the composite's performance [8–11]. Hence, characterizing the effects of environmental degradation, including the synergistic effects of temperature, heat, and oxygen, is necessary to predict long-term performance, supporting the design phase of composite structures. Accelerated aging studies at the full-scale level are generally challenging to conduct because of the related cost; therefore, accelerated aging studies at the coupon/material level are more common to assess the long-term behavior of composites in laboratory settings [12].

The temperature dependence of the structural properties of fiber-reinforced polymers (FRPs) composites could be divided into short- and long-term effects [13]. Previous studies on thermal aging showed that degradation is an energy-activated process and is caused by the synergistic effect of heat and oxygen (thermo-oxidative aging). Microstructural changes due to aging, such as matrix cracking [11], fiber-matrix debonding [14], and physicochemical changes like increased cross-linking density [15] due to residual post-curing,

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are observed. These physical and chemical changes could lead to alterations in mechanical performance, which would effect the long-term structural integrity. Reversible changes like plasticization of matrix [16], observed during the synergistic effect of temperature and moisture, should be distinguished from non-reversible phenomena like yellowing due to carbonyl conversion [17], oxidation-induced weight loss [18], and fiber/matrix interfacial degradation [19]. The effect of thermal aging is a competing process. There is an interplay between degradation and post-curing. During the initial days of aging, effects like residual post-curing of the matrix are dominant, leading to an eventual increase in the properties and causing the so-called "strengthening/consolidation" phase. During the initial days of aging, a "consolidation phase" is visible, where properties increase due to residual curing in the presence of curing agents like styrene. After prolonged exposure to higher temperatures, matrix-dominated properties like shear [20–22] and Tg [23–25] are primarily affected [26–28]. Thermal aging has also been found to cause micro-cracking, hazing (especially for above-Tg exposure), thermal decomposition, or even charring [27].

The reaction kinetics of the thermal degradation depend on the structure of the polymer and have been reported to occur in three steps: (1) initiation, where free radicals and hydrogen atoms are created by disassociation in the presence of heat; (2) propagation, where the free radicals attack the oxygen molecules to create peroxide radicals. This is followed by addition reactions to create hydroperoxide radicals, which produce water and more free radicals by the process of recombination, and (3) termination, where unpaired free radicals combine and release oxygen [29]. Thus, the process is thermo-oxidative. It is worth noting that peroxide radicals can also be present in the cured matrix due to incomplete polymerization during processing [28], which may also positively catalyze the reaction kinetics. The term "induction period" is often used for composite structures deployed at above ambient temperature environments, which defines a structure's usable period or lifetime, after which the thermo-oxidative aging rapidly increases. Thus, being able to accurately predict the induction period is of primary importance, as it is linked to performance prediction and significant for designing failure criteria.

Performance prediction of composites

The exposure of the composite material to elevated temperatures can severely degrade its mechanical properties over the long term. Nonetheless, the material's strength and moduli may increase in the initial aging period due to potential post-curing. However, for prolonged exposure periods, mechanical properties eventually diminish. As such, the prediction of long-term behavior is of primary importance. The earliest and most common predictive model to account for single-environment and energy-activated processes (thermal aging in this work) is the Arrhenius rate degradation model [30]. Arrhenius modeling has been employed here to predict the residual properties of the aged composite coupons as a function of exposure temperature and service life.

Arrhenius prediction model

The Arrhenius degradation model has been empirically used to predict the service life of composites [13, 29, 31]. The degradation model was created by the Swedish chemist Svante Arrhenius in 1887 for the chemical reaction kinetics $R(t)$, as a function of the temperature (T) in Kelvin and is given by:

$$R(t) = A\exp\left[\frac{-E_a}{RT}\right]$$

where R is the universal gas constant (8.314 J/mol K), E_a is the activation energy, and A is the non-thermal constant. To predict the residual properties as a function of the aging temperature, the Arrhenius stress-life relationship can be formulated, where it is assumed that the residual properties are inversely proportional to the reaction rate of the process. The relationship can then be expressed as:

$$L(T) = C\exp\left(\frac{B}{T}\right)$$

where $L(T)$ is the material property, C is the positive material parameter determined by regression analysis, B is the ratio of activation energy and universal gas constant, and T is the temperature in Kelvin (K). The relationship can be linearized by taking natural logarithms on both sides and can be expressed as:

$$\ln\left(L(T)\right) = \ln(C) + \frac{B}{T}$$

B is the gradient, $\ln(C)$ is the intercept on the y-axis, and the horizontal axis is the inverse of the temperature (T), the variable in the equation. An equivalence can be drawn for B from the Arrhenius equation, and it has the same properties as the activation energy (E_a). Thus, the higher the value of B, the more pronounced the effect of the stressing factor (e.g. temperature) and, thus, the dependency of the residual properties on the stress factor (temperature). It is also stressed that the temperature solely changes the reaction kinetics, and no new degradation mechanisms occur. Thus, the thermal degradation of the composite is an energy-activated process. Stress-life plots can be created by plotting the inverse of temperature and the percentage retention of residual properties from the experimental data. Regression analysis can be used to create the stress-life relationship equations at one temperature and can be extrapolated to other aging temperatures. The Arrhenius method has the limitation that, when the degradation mechanisms change with the change in temperatures, it is not possible to use the simple time-temperature superposition, as the method is non-mechanistic in nature. Though good experimental correlation can be obtained if the former condition is fulfilled [32].

In this work, we predict the long-term behavior of filament wound glass fiber/vinylester composite coupons when subjected to sub-Tg thermal aging environments. The aging protocol was designed to perform thermal aging at sub-Tg temperatures of 23°C, 40°C, 60°C, and 80°C, simulating real service conditions in hot and dry climates. The maximum temperature of 80°C (≈20% below Tg of vinylester) was chosen to inhibit unrealistic macromolecular mobility and avoid any viscous inherent structural transformations. The mechanical properties of the composite were studied as a function of aging duration and temperature levels, where coupons were tested at 28, 56, 112, and 224 days. Residual property values were calculated and used to predict the performance over time using the Arrhenius prediction modeling approach. A comparison was made with the experimental findings, predicted properties, and the standard error in the observation for a service life of 40 years.

Experimental program and aging

Test coupons were extracted along the axial direction of a tubular section, as presented in Figure 14.1, with an average glass fiber volume fraction of 70±2% measured from calcination. The samples were wet-cut using an ATM Brilliant wet-cutting machine. The coupons were then thermally aged in a convection oven at 40°C, 60°C, and 80°C ($0.8T_g$) temperature levels. For room-temperature aging (23°C), the samples were kept in a closed box with silica beads inside a temperature-controlled lab environment. Samples were tested for short beam shear (SBS) and flexure response, following ASTM D2344 and ASTM D7264 test standards, after aging for 28, 56, 112, and 224 days. Mechanical testing was performed on an Instron 5966 universal testing machine with a 10 kN maximum capacity. For SBS testing, the span length was 22 mm, nearly four times the average thickness of the coupon. The interlaminar shear strength (ILSS) was calculated using Equation (14.1)

$$\tau = 0.75\frac{P_{\mathrm{m}}}{bh} \tag{14.1}$$

where P_{m} is the maximum load from the load-displacement curve, and b and h are the width and thickness of the FWCs coupon. In the case of flexure testing, the span length was set to 80 mm, with a span-to-thickness ratio of 16:1. The loading rate was set to 1 mm/min for both testing regimes. The flexural stiffness was calculated as the slope of the initial elastic region of the flexural

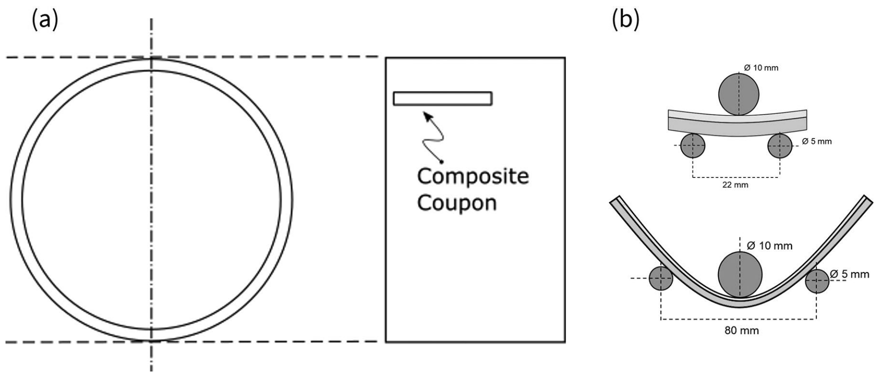

Figure 14.1 (a) The cross-section of cylindrical filament wound composite (FWC) and coupon extraction (b) Schematic of SBS/flexural mechanical testing. (top) ILSS test (bottom) flexural test setup.

Table 14.1 Test specimens for isothermal aging and mechanical property measurement

Test	*Standard*	*Specimen No.*	*Size [mm]*
SBS	ASTM D2344	temp(4) × time(4) × Rep(5) + Unaged(5) = 85	30 × 13 × 5
Flexure	ASTM D7264	temp(4) × time(4) × Rep(5) + Unaged(5) = 85	140 × 15 × 5
Total		170	

stress (σ)- strain(ε) curve. The maxima of the stress-strain curve were selected as flexural strength values, as presented in Equation (14.2)

$$\sigma = \frac{3PL}{2bh^2} \quad \varepsilon = \frac{6\delta h}{L^2} \tag{14.2}$$

where P is the force (kN), L is the span length, and δ is the mid-span deflection. A summary of the number of coupons, dimensions, and mechanical testing standards is presented in Table 14.1.

Results and discussion

Figures 14.2–14.4 present the effects of thermal aging on ILSS and flexural performance as a function of exposure temperature and aging duration. It was observed that the mechanical behavior of the composite coupons during the aging regime was sigmoidal, and two-phase evolution was observed. As the aging was performed below the glass transition temperature, resin-dominated properties are critical in determining the coupons' behavior [33]. The effects of

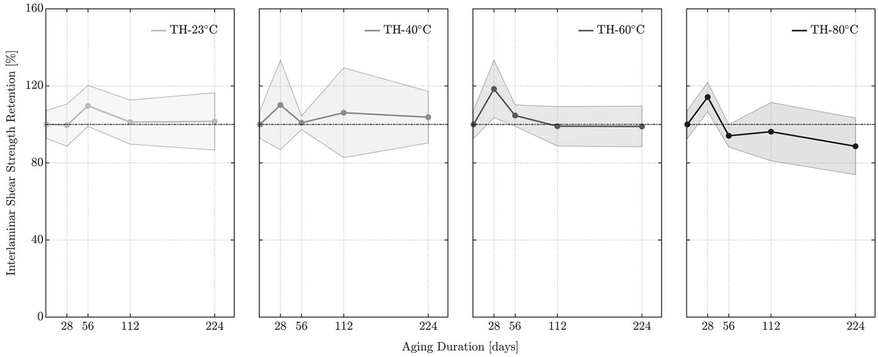

Figure 14.2 ILS strength retention of FWC exposed to iso-thermal aging.

aging can be categorized between the time frame "0" (unaged)-56 days and 56 days to 224 days due to the two-phase evolution.

In the case of SBS coupon testing, during the initial days of aging, ILS strength values for all aging regimes increase. A higher intensity of "strengthening" was visible for aging above room temperature (23°C). The composite reaches optimal design properties due to strengthening, and the aging temperature strongly influences this increase. For aging at room temperature, the maximum strengthening is observed at 56 days, whereas for the remaining aging temperature cases, the maximum strengthening is observed early at 28 days.

This strengthening effect can be attributed to additional cross-linking inside the vinylester matrix, hence causing an increase in the ILSS values (which is a matrix-dominated property). A time-temperature coupling is visible between 0 and 56 days of aging, where higher temperature leads to faster rearrangement of molecular chains and additional cross-linking due to an increase in reaction kinetics, as also reported by Marouani et al. [34]. For composite specimens aged at 23°C, 40°C, and 60°C, ILS strength values plateau after the initial strengthening, without noticeable degradation of ILS strength until the end of the aging duration of 224 days. For aging at 60°C, the increase in ILS strength is higher in magnitude than for aging at lower temperatures. In the case of aging at 80°C, an interplay of cross-linking and degradation might be hypothesized, wherein the strengthening is recorded at 28 days of aging, followed by a monotonous decrease in the ILS strength, to lower retention values than the unaged coupons.

For the case of flexural testing, for aging at 23°C, 40°C, and 60°C temperature levels, a strengthening in the flexural strength is observed, which could be again attributed to increased cross-linking, as also reported by [10, 20, 35–37] as presented in Figure 14.3. For temperatures greater than 60°C, the onset of degradation starts early, and it can be hypothesized that

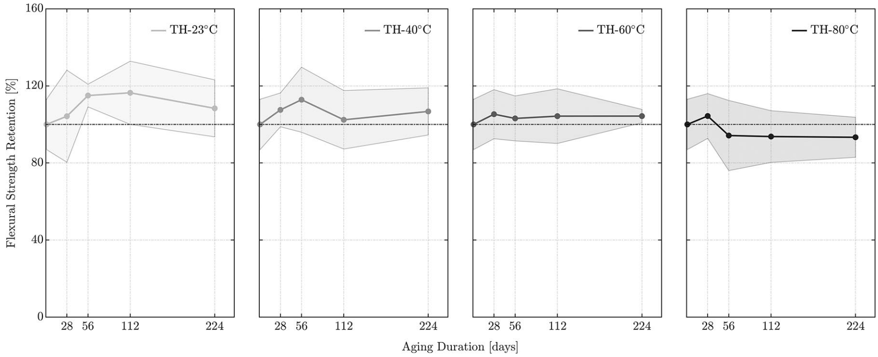

Figure 14.3 Flexure strength retention of FWC exposed to iso-thermal aging.

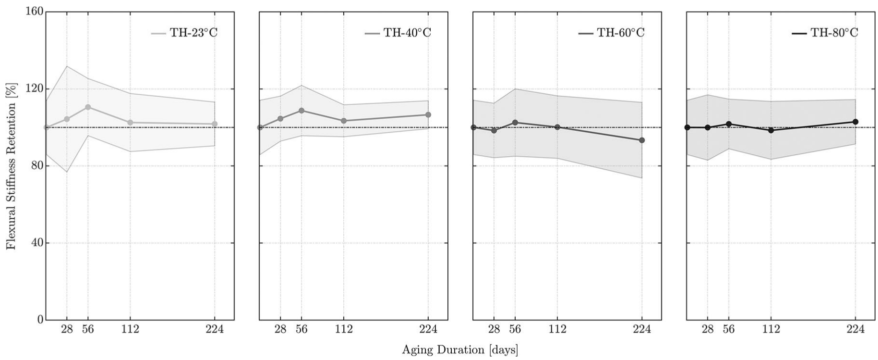

Figure 14.4 Flexure stiffness retention of FWCs exposed to iso-thermal aging.

the lower levels of strengthening in property could be a result of competing mechanisms of chain scission and cross-linking. Degradation is observed for aging at 80°C, where the properties reduce by nearly 5% during the onset of degradation after 56 days of aging.

Figure 14.4 presents the variation in the flexural stiffness values, which are dominated by fiber failure and fiber/matrix interfacial failure [10, 20]. It is observed that for aging at 23°C and 40°C, a slight increase in the stiffness values was observed after the complete duration of 224 days. At higher temperatures of 60°C and 80°C, the flexure stiffness of the FWCs coupons starts to reduce from the initial strengthening, but plateaus. It can be stipulated that thermal aging is an energy-activated process that does not significantly affect the fibers or the fiber/matrix interface.

To discuss the effects on the ILS and flexure properties, it can be concluded that a higher reduction in the ILS strength is observed at higher temperatures of 60°C and 80°C, close to the vinyl ester's glass transition temperature.

At lower temperatures, the ILS strength plateaus. At the end of the aging regime, except at 80°C, no degradation is observed for the remaining combinations of aging temperatures and duration. Longer exposure of the composite coupon caused matrix embrittlement and leads to thermal stresses between the fiber and matrix due to a difference in the thermal expansion coefficient between the fiber and matrix. This differential thermal expansion might lead to micro-cracks forming, which act as sites for delamination and stress cracking, as reported by Hota et al. [13]. The creation of the micro-cracks during aging also helps create crevices where oxygen can percolate, thus leading to oxidation in the bulk of the polymer.

The flexure strength of the composite materials is also dependent on the matrix, as defects like cracks in the matrix and delamination could act as sites for crack initiation and propagation [38]. However, for FWCs, it has been hypothesized by Gong et al. [39] that in the presence of fibers in the hoop layer parallel to the surface of the composite, the diffusion of oxygen is arrested, which protects the bulk of the coupon to remain unaffected. The flexural stiffness and the strength both observe a slight reduction in the overall properties at the end of the aging regime, but a pure degradation phase is observed at 80°C in the strength of the composite coupons. Karbhari [40] observed that the higher temperature exposure leads to micro-cracks both at the surface and bulk; hence, a reduction in the eventual flexure strength of the composite is observed. It can be summarized from the aging and testing protocols that matrix-dominated properties like ILS strength and flexure strength degrade much faster than fiber-dominated properties like the flexural stiffness of the aged composite.

The calculated experimental scatter of the flexural stiffness and strength values is higher than that of the ILS strength. This could be due to the mixed mode of failure in the flexure tests, where the failure behavior is a combination of the fiber/matrix interface interaction and matrix failure under the compression zone of the loading pin [10] and the local fiber orientation. Tables 14.2–14.4 summarize all mechanical property test data as a function of time and aging temperature.

Table 14.2 ILS strength retention as a function of temperature time after isothermal aging

Time [days]	*ln(time)*	*Residual interlaminar shear strength (%) ± standard deviation*			
		23°C/296 K	*40°C/313 K*	*60°C/333 K*	*80°C/353 K*
Unaged	---	100			
28	3.33	99.6 ± 10.8	110.1 ± 23.2	118.4 ± 14.8	114.2 ± 7.5
56	4.02	109.6 ± 10.6	100.8 ± 3.5	104.6 ± 5.5	94.1 ± 5.8
112	4.71	101.2 ± 11.4	106.1 ± 23.2	99.1 ± 10.2	96.2 ± 15.1
224	5.41	101.5 ± 14.8	103.7 ± 13.3	98.9 ± 10.5	88.6 ± 14.7

Table 14.3 Flexure strength retention as a function of temperature time after isothermal aging

Time [days]	*ln(time)*	*Residual flexural strength (%)*			
		23°C/296 K	*40°C/313 K*	*60°C/333 K*	*80°C/353 K*
Unaged	---	100			
28	3.33	104.2 ± 23.8	107.5 ± 8.7	105.3 ± 12.7	104.3 ± 11.6
56	4.02	114.9 ± 5.8	112.8 ± 16.8	103.1 ± 11.6	94.2 ± 18.1
112	4.71	116.4 ± 16.3	102.4 ± 15.1	104.3 ± 14.1	93.7 ± 13.4
224	5.41	108.3 ± 14.7	106.7 ± 12.2	104.3 ± 3.4	93.3 ± 10.3

Table 14.4 Flexure moduli retention as a function of temperature time after isothermal aging

Time [days]	*ln(time)*	*Residual flexural moduli (%)*			
		23°C/296 K	*40°C/313 K*	*60°C/333 K*	*80°C/353 K*
Unaged	---	100			
28	3.33	104.3 ± 27.4	104.5 ± 11.6	98.4 ± 14.1	100 ± 16.9
56	4.02	110.5 ± 14.8	108.7 ± 13.1	102.5 ± 17.4	101.8 ± 12.8
112	4.71	102.5 ± 15.1	103.4 ± 8.2	100.1 ± 16.2	98.4 ± 15.1
224	5.41	101.8 ± 11.3	106.5 ± 7.2	93.36 ± 19.6	102.9 ± 11.5

Arrhenius prediction model

The mechanical test data was presented as percentage retention as a function of time and temperature. The relationship between time and the percentage retention in the mechanical parameter is linearized by taking a natural logarithm of the Arrhenius model. This study used a second-order polynomial fit to achieve a higher R-square value due to the high strengthening observed during the initial days of aging. The regressed polynomial equation can be used to predict the response at a specific time during the aging of the composite material. The Arrhenius rate degradation model can then be used at a specific temperature by substituting the predicted material property.

Figure 14.5 presents the ILS retention curve predicted by rate degradation and the experimental values for comparison exposed to 23°C, 40°C, 60°C, and 80°C. Except for the aging at 23°C, the prediction correlates well with the experimental values, as the curve falls within the standard deviation. The ILS strength values showed an initial increase during the "consolidation phase" and then decreased and leveled off. The model predicts only a strengthening phase for aging at 23°C and then levels off. This is due to the experimental values falling above 100% and exhibiting no degradation. Table 14.5 presents the percentage error in the predicted values, and it can be observed that the average error is less than 10%, with higher confidence in

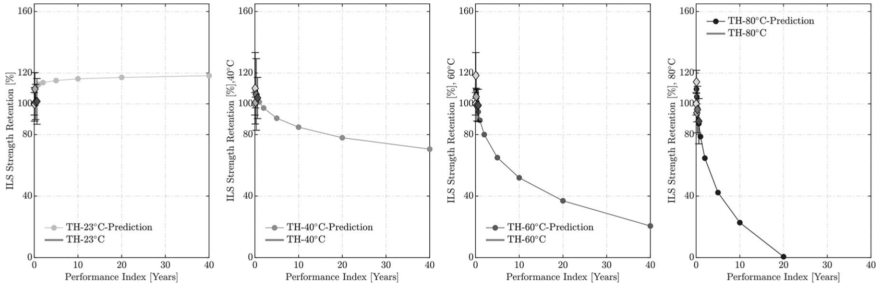

Figure 14.5 ILS strength retention extrapolated to 40 years. Using the Arrhenius rate degradation model.

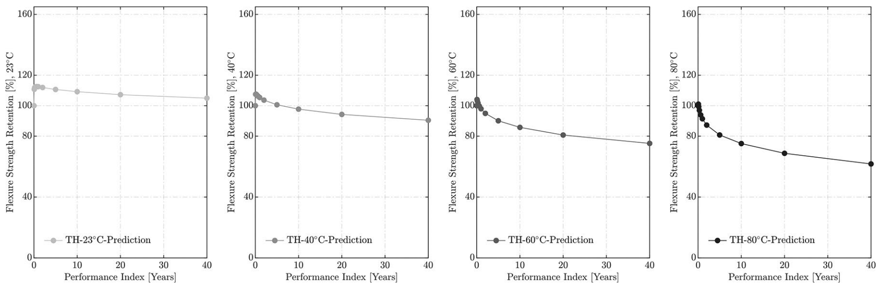

Figure 14.6 Flexural strength retention extrapolated to 40 years. Using the Arrhenius rate degradation model.

prediction at higher temperatures due to degradation and Arrhenius being an exponentially increasing or decreasing function.

Figure 14.6 and Table 14.6 present prediction results from the Arrhenius rate degradation model for the residual flexural strength values. The model predicts strengthening during and after the experimental aging regime duration. As the temperature and the aging duration increase, strength reduction is observed. Time-temperature coupling is again observed, with the highest reduction at 80°C at the end of the 40 years, considering material degradation over time. Comparing all three mechanical property values, it can be observed that the degradation in the ILS and flexure strength is highest compared to the flexure stiffness. This can again be attributed to the former being a matrix-dominated property, thus affected primarily by isothermal aging.

Figure 14.7 and Table 14.7 present the variation in the predicted flexural moduli and percentage error as a function of the aging duration and temperature. The rate degradation presents a similar behavior to the ILS strength, where the values decrease and then level off. The predicted values are higher in comparison to values observed at low temperature aging. This can be

Table 14.5 ILS strength retention, prediction, and percentage error calculated from the Arrhenius rate degradation model

Days	23°C			40°C			60°C			80°C		
	Exp.	*Pred.*	*Error*	*Exp.*	*Pred.*	*Error*	*Exp.*	*Pred.*	*Error*	*Exp.*	*Pred.*	*Error*
0	100											
28	99.6	107.7	8.1	110.1	108.3	−1.6	118.4	108.9	−7.9	114.2	109.5	−4.1
56	109.6	109.1	−0.4	100.8	107.6	6.7	104.6	105.9	1.3	94.1	104.5	11.1
112	101.2	110.4	9.1	106.1	105.9	−0.6	99.1	101.2	2.1	96.2	96.9	0.7
224	101.5	111.7	10.0	103.7	103.4	−0.3	98.9	94.8	−4.2	88.6	87.1	−1.7
365	–	112.6	–	–	101.2	–	–	89.2	–	–	78.6	–
730	–	113.8	–	–	97.2	–	–	79.9	–	–	64.6	–
1825	–	115.1	–	–	90.6	–	–	65.0	–	–	42.2	–
3650	–	116.2	–	–	84.8	–	–	51.2	–	–	22.7	–
7300	–	117.1	–	–	77.9	–	–	36.9	–	–	0.5	–
14600	–	118.2	–	–	70.5	–	–	20.5	–	–	–	–

Table 14.6 Flexure strength retention, prediction, and percentage error calculated from the Arrhenius rate degradation model

Days	23°C			40°C			60°C			80°C		
	Exp.	*Pred.*	*Error*	*Exp.*	*Pred.*	*Error*	*Exp.*	*Pred.*	*Error*	*Exp.*	*Pred.*	*Error*
0	100											
28	104.2	110.7	6.2	107.5	107.4	−0.1	105.3	104.1	−1.2	104.3	101.0	−3.2
56	114.9	111.8	−2.7	112.8	107.6	−4.6	103.1	103.2	0.1	94.2	99.3	5.4
112	116.4	112.4	−3.4	102.4	107.2	4.6	104.3	101.7	−2.4	93.7	96.9	3.4
224	108.3	112.6	3.9	106.7	106.3	−0.4	104.3	99.8	−4.3	93.3	93.9	0.6
365	–	112.5	–	–	105.3	–	–	97.9	–	–	91.4	–
730	–	111.9	–	–	103.6	–	–	94.9	–	–	87.2	–
1825	–	110.6	–	–	100.6	–	–	90.1	–	–	80.7	–
3650	–	109.2	–	–	97.7	–	–	85.7	–	–	75.1	–
7300	–	107.2	–	–	94.2	–	–	80.7	–	–	68.7	–
14600	–	104.9	–	–	90.4	–	–	75.2	–	–	61.7	–

Table 14.7 Flexure moduli retention, prediction, and percentage error calculated from the Arrhenius rate degradation model

Days	*23°C*			*40°C*			*60°C*			*80°C*		
	Exp.	*Pred.*	*Error*	*Exp.*	*Pred.*	*Error*	*Exp.*	*Pred.*	*Error*	*Exp.*	*Pred.*	*Error*
0	100											
28	104.3	107.3	2.9	104.5	104.8	0.2	98.4	102.1	3.8	100	99.8	−0.2
56	110.5	106.7	−3.4	108.7	104.2	−4.1	102.5	101.5	−1.1	101.8	99.1	−2.6
112	102.5	105.5	2.9	103.4	103.1	−0.3	100.1	100.5	0.3	98.4	98.2	−0.2
224	101.8	103.5	1.7	106.5	101.3	−4.8	93.3	99.1	6.2	102.9	97.0	−5.6
365	–	101.7	–	–	99.8	–	–	97.9	–	–	96.2	–
730	–	98.5	–	–	97.2	–	–	95.9	–	–	94.7	–
1825	–	93.1	–	–	92.9	–	–	92.6	–	–	92.4	–
3650	–	88.3	–	–	89.0	–	–	89.7	–	–	90.4	–
7300	–	82.7	–	–	84.6	–	–	86.5	–	–	88.2	–
14600	–	76.4	–	–	79.5	–	–	82.8	–	–	85.8	–

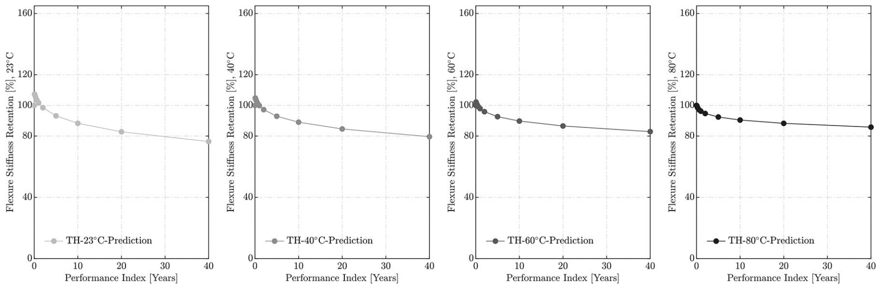

Figure 14.7 Flexural moduli retention extrapolated to 40 years. Using the Arrhenius rate degradation model.

attributed to the experimental values, which start to increase toward the end of the experimental aging period of 224 days.

Summary

In this work, FWC coupons were aged thermally at four aging temperatures (23°C, 40°C, 60°C, and 80°C), which are sub-T_g, for a total duration of 224 days. Coupons were tested mechanically, at four different time intervals, specifically after 28, 56, 112, and 224 days of aging. Experimental data were employed to develop lifetime prediction curves via Arrhenius modeling. The main outcomes of this research work are:

1 In all test cases, a strengthening-effect in mechanical properties was revealed, after short-term aging (i.e., 0–56 days), which could be attributed to residual post-curing and an increase in the cross-linking density.
2 A time-temperature coupling was observed for the aging regime, where higher aging temperature levels lead to degradation during the early days of aging and lower aging temperature levels cause strengthening in the properties.
3 The post-curing effect on matrix-dominated properties like ILS strength and flexure strength was more prominent as compared to flexural stiffness.
4 No strengthening in properties was observed during the long-term aging (i.e., 112–224 days) where the material degrades ($P(t)$ < 100%) at high temperatures for ILS and flexure strength retention. Mechanical properties plateau close to the unaged material when samples are aged well below the Tg (23°C, 40°C, and 60°C) and for 224 days of aging.
5 The prediction based on the Arrhenius rate degradation model falls within the standard deviation for the mechanical testing experimental curves, has a relatively lower error percentage, and hence can be applied for the determination of long-term performance, though the estimates are conservative, so design calculations should be made with caution.

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Chapter 15

SFI Manufacturing – facts

A multi-disciplinary centre for research-based innovation in manufacturing.

A collaborative joint venture between the Research Council of Norway, 3 research institutes from the SINTEF group, the Norwegian University of Science and Technology, and 15 manufacturing companies:

- Benteler Automotive Raufoss AS
- Brødrene Aa AS
- Hapro Electronics AS
- Hexagon Ragasco AS
- GKN Aerospace Norway AS
- Ekornes ASA
- HyBond AS
- Kongsberg Automotive AS
- Kongsberg Gruppen ASA
- Mjøs Metallvarefabrikk AS
- Nammo Raufoss AS
- Norsk Hydro ASA
- Raufoss Technology AS
- Sandvik Teeness AS

The centre period has been 2015–2023, and the total budget was 202 million NOK (~EUR 18,000,000). The host institution has been SINTEF Manufacturing.

The vision of the centre has been "To show that sustainable and advanced manufacturing is possible in high cost countries, with the right application, technologies and humans involved."

The centre's research has been organised on tree research areas:

- Multi-material products and processes
- Robust and flexible automatisation
- Innovative and sustainable organisations

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Figure 15.1 The logo of SFI Manufacturing.

During the centre period, the centre has delivered:

- Education of 16 PhD students, 4 postdocs and more than 50 master degree students
- More than 200 scientific prereview publications
- Approximately 60 scientific results with identified innovation potential
- Spin-off innovation activities with a total budget exceeding 1.3 billion NOK (~EUR 115,000,000)

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