Enablers and Tools for Agile Product Development

20

Thomas Kaster, Marc Ackermann, David Bailly, Marie-Noemi Bold,
Thomas Bremen, Thomas Eberius, Cailing Fu, Leon Gorißen,
Christian Haase, Thomas Gries, Constantin Leon Häfner,
Christian Heinigk, Christian Hinke, Gerhard Hirt, Carlo Holly,
Hannah Kelbel, Moritz Kolter, Ulrich Krupp, Lisa-Marie Reitmaier,
Johannes Henrich Schleifenbaum, Günther Schuh,
Wolfgang Schulz, Lena Stöcker, Philipp Walderich, and Omid Zarei

Contents

T. Kaster (✉) · L. Gorißen · C. L. Häfner · C. Hinke · P. Walderich
Laser Technology (LLT), RWTH Aachen University, Aachen, Germany
e-mail: thomas.kaster@llt.rwth-aachen.de; leon.gorissen@llt.rwth-aachen.de;
constantin.haefner@llt.rwth-aachen.de; christian.hinke@llt.rwth-aachen.de;
philipp.walderich@llt.rwth-aachen.de

M. Ackermann · C. Haase · U. Krupp
Steel Institute (IEHK), RWTH Aachen University, Aachen, Germany
e-mail: marc.ackermann@iehk.rwth-aachen.de; christian.haase@iehk.rwth-aachen.de;
krupp@iehk.rwth-aachen.de

C. Brecher et al. (eds.), *Internet of Production*, Interdisciplinary Excellence
Accelerator Series, https://doi.org/10.1007/978-3-031-44497-5_18

Abstract

Today's industrial world is characterized by ever-shortening product development cycles and increasing degrees of product individualization which demand tools and enablers for accelerated prototyping. In addition, the existing uncertainty in the product development cycle should be reduced by involving stakeholders as early as possible. However, should an engineering change request (ECR) be necessary in the product development cycle, a fast iteration step into production is inevitable. The methodological description of such an ECR in the product development cycle is described in the previous chapter. Together with researchers from the Internet of Production (IoP), information from the product development process will be transferred to the digital shadow established in the IoP. The digital shadow collects information from all areas of the product lifecycle and provides it to the appropriate departments, adapted to the corresponding task. To tackle this challenge, a new type of product development process, the method of agile product development, is applied. Within the Enablers and Tools project, the development of various advanced manufacturing technologies (AMTs) for agile product development are at the forefront of the work. The enablers and tools are further developed with the principles of agile product development. They also serve to map the

---

D. Bailly · T. Bremen · G. Hirt · L.-M. Reitmaier
Institute of Metal Forming (IBF), RWTH Aachen University, Aachen, Germany
e-mail: david.bailly@ibf.rwth-aachen.de; thomas.bremen@ibf.rwth-aachen.de; gerhard.hirt@ibf.rwth-aachen.de; lisa-marie.reitmaier@ibf.rwth-aachen.de

M.-N. Bold · M. Kolter · O. Zarei · J. H. Schleifenbaum
Institute for Digital Additive Production (DAP), RWTH Aachen University, Aachen, Germany
e-mail: marie-noemi.bold@dap.rwth-aachen.de; moritz.kolter@dap.rwth-aachen.de; johannes.henrich.schleifenbaum@dap.rwth-aachen.de; omid.zarei@dap.rwth-aachen.de

T. Eberius · G. Schuh · L. Stöcker
Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Aachen, Germany
e-mail: t.eberius@wzl.rwth-aachen.de; g.schuh@wzl.rwth-aachen.de; l.stoecker@wzl.rwth-aachen.de

C. Fu · C. Holly
Technology of Optical Systems (TOS), RWTH Aachen University, Aachen, Germany
e-mail: cailing.fu@tos.rwth-aachen.de; carlo.holly@tos.rwth-aachen.de

T. Gries · H. Kelbel
Institute of Textile Technology (ITA), RWTH Aachen University, Aachen, Germany
e-mail: thomas.gries@ita.rwth-aachen.de; hannah.kelbel@ita.rwth-aachen.de

C. Heinigk · W. Schulz
Nonlinear Dynamics of Laser Manufacturing Processes (NLD), RWTH Aachen University, Aachen, Germany
e-mail: christian.heinigk@nld.rwth-aachen.de; wolfgang.schulz@nld.rwth-aachen.de

requirements for rapidly available and specific prototypes which are used to answer specific questions that arise during the product development cycle. To answer these questions, the concept of the Minimum Viable Product (MVP), an approach to reduce development time and increase customer satisfaction, is introduced and applied to all development tasks.

20.1 Introduction

Manufacturing companies continue to account for a high share of added value in Germany (Statistisches Bundesamt 2022). At the same time, companies are dependent on stable framework conditions. Changes in the framework conditions, e.g., due to changed value chains, rising raw material prices, or changes in consumer behavior, pose particular challenges for manufacturing companies (Brecher et al. 2017). In this context, sustainable corporate success is only possible through innovative products due to global competition (Schuh et al. 2017). To meet this challenge, flexible production processes and fast and efficient product development are required (Brecher et al. 2017).

To establish faster product development processes, the Enablers and Tools for agile product development subproject is investigating how the principles and methods of agile product development can be transferred to manufacturing companies. Agile product development methods are characterized in particular by the fact that uncertainties in the product development process can be reduced at an early stage through the early involvement of stakeholders. The new role of prototypes, in which prototypes are to answer specific questions in the product development process, also serve to reduce the uncertainty in the product development process. In this context, the subproject investigates how the maturity and execution level of prototypes can be determined in order to be able to answer specific questions (Schuh 2017).

For the meaningful and rapid production of these prototypes, enablers and tools are needed that can produce prototypes quickly and under the given boundary conditions. One major focus of the project is the further development of so-called advanced manufacturing technologies (AMTs) and how AMTs and data acquired from prototyping technologies can be used for agile product development. The second focus is the use of all relevant data from production and material to determine the minimum viability of a product prototype as well as to select, adapt and improve the respective prototyping technologies. In the long term, all relevant data provided shall be integrated into automated and interactive design tools to support continuous stakeholder integration as well as latency elimination for agile product development.

The following section describes the state of the art in agile product development and AMTs. Subsequently, the AMTs investigated in the subproject, such as 4D-textiles, additive manufacturing or robot-based laser material processing and interactive tools such as the automated design of optical systems, are presented.

20.2 State of the Art

Agile process methods are adaptive approaches originally used in software development and are characterized by an iterative development process. In each cycle with a defined length, increments are generated and validated by the customer. The strong involvement of the customer enables the development process to react proactively to new requirements. The development process is characterized by informal communication (Goll 2015). These methods aim to counteract the deficits of a requirements analysis at the beginning of a development project and allow an earlier usage of preliminary versions of the (software) product (Sommerville 2010).

The basis of agile process methods is the "Agile Manifesto" which defines four guiding values and 12 principles to aid implementation of agile methods into development processes, accepting the limited plannability of complex processes (Highsmith and Fowler 2001).

Defining characteristics of agile methods are (Sommerville 2010):

- **Flexibility and transparency**: Processes are designed efficiently and superfluous work steps are avoided as far as possible
- **Focus on people**: Processes are aligned according to the people involved and their capabilities. Developers work independently in close cooperation and are freed from strict procedural requirements
- **Involvement of the customer**: The customer is regularly involved in the development process. The customer's task is to review the development process and help shape the further procedure
- **Accommodating change**: Changes are welcomed and actively addressed by developers
- **Iterative development**: The process is characterized by recurring activities
- **Incremental delivery**: Functional product increments are delivered to the customer at regular intervals. New requirements for the product are implemented with each delivery

In comparison to conventional development methods, the development cycles and the lead time to a marketable product are shortened significantly and the customer can intervene early since deviations between understanding of customer and developing team are detected at an early stage (Sommerville 2010). After each iteration cycle, the customer has a potentially applicable prototype. The Minimum Viable Product (MVP) is usable by early customers who can provide feedback for further product development.

Advanced manufacturing technologies (AMT) such as additive manufacturing (AM) allow an efficient transformation from digital design data into physical products and present a growing field of international research (Behera et al. 2013). Especially metal AM is of growing interest and several international research groups are working on this topic (Baumers et al. 2016; Zaeh and Ott 2011). While focused on solving the dilemma between scale and scope, i.e., enhancing process efficiency and quality, there is very little research on integrating advanced manufacturing technologies into agile product development processes. Technical limitations and the systematic deviations between AMT and conventional manufacturing technologies (e.g., spring-back for Incremental Sheet Forming or resulting microstructure for AM) restrict a wider use of AMT for functional prototypes.

Advanced manufacturing technologies typically provide a new "freedom of design" (e.g., lattice structures by AM, functional surface structures by laser ablation, or complex patterns by 3D-weaving) which results in a multi-scale problem. To adopt a product or component to specific functional requirements, thousands or millions of lattice or surface structures must be adopted to these requirements. Due to the increased design effort and the according lead-time, the potential of such functional adopted multi-scale structures cannot be fully utilized today. Therefore, we currently face a growing international research in the field of automated or generative design (Panesar et al. 2018; Wu et al. 2015).

One way of implementing agile techniques from software development into physical product development involves recording the work steps in the previous product development and defining suitable agile techniques as a replacement model in each case. Product development is carried out in an agile manner using the substitute models and finally merged into a complete process model (Kantelberg 2018; Klein 2016). Step 1 is used to capture the original product development process to identify the activities, decisions, and interactions of the stakeholders in the individual development steps. The development sub-steps are decomposed to define their modes of action based on processes, activities, tools, and roles. In step 2, a suitable agile technique such as Scrum is selected. The procedure is divided into processes, activities, tools, and roles, analogous to the previous product development process. In step 3, the processes, activities, tools, and roles of the two product development processes are transferred from the previous to agile product development in tabular form. Activity and decision maps as well as profiles of the agile techniques can be used as an aid. Agile submodels are assembled to form the rough concept of the workflow for physical product development (step 4), and product development is carried out in an agile manner using the developed concept (step 5) (Kantelberg 2018; Klein 2016).

By applying this general workstream, agile techniques can help enable a faster and more efficient product development process in the physical world. In the following chapters, examples of suitable AMTs and possible applications in the context of agile product development are presented. For each AMT, usage and integration of the technology and data acquired during manufacturing in agile development environments is explored. Also, the use of relevant data from production and material to determine the minimum viability of a product prototype as well as to select, adapt and improve the according prototyping technologies is investigated.

20.3 Contributions

20.3.1 Innovative Kinematic Systems for Laser Material Processing

In recent years, lasers have been established as a manufacturing tool with a wide variety of production processes, such as laser cutting, laser welding, or laser structuring in production technology (Hügel 2009; Poprawe 2005). Photonic technologies are also considered enablers for global environmental sustainability (BMBF 2018; Cochard and d'Humières 2019; Poprawe 2019). Furthermore, laser technology can be seen as a particularly flexible process that is suitable for the rapid and cost-effective production of prototypes and small series, also in the context of agile product development (Hinke 2018; Poprawe 2005). To apply laser technology in material processing, a relative motion between the laser tool and the material to be processed must be realized. This relative motion is typically implemented via kinematic systems that have been adapted from other manufacturing processes. Accordingly, these kinematic systems are not optimized for the requirements of laser technology and do not exploit the advantages of laser technology. Within the subproject, the suitability of new, innovative kinematic systems for laser material processing (LMP) is systematically investigated. With these new kinematics systems, LMP can be used as an enabler for agile product development in science and industry (Poprawe 2005).

Due to the non-contact processing of workpieces by laser radiation, no restoring forces act on the kinematic systems (Hügel 2009). Accordingly, the kinematic systems do not have to absorb these forces and can be designed to be less rigid than for other manufacturing processes, such as milling (Cen et al. 2016). As a result, flexible kinematics systems such as robots are suitable for LMP. The challenge here is that current, low-cost robotic systems do not meet the accuracy requirements.

The aim of the project is to investigate the potential of LMP with respect to new kinematic systems. For this purpose, concepts for new kinematic systems will be developed and their suitability for LMP will be investigated. The focus of the work is on increasing the accuracy of the kinematic systems. The kinematic systems are not developed to series production readiness, but the suitability of the systems in principle for LMP is investigated with prototypes via proof of concept. Currently, this is being investigated on two different prototypes.

The prototypes are themselves being developed using agile product development methods and each represents a Minimum Viable Product (MVP). For flexible 3D machining of components by using low-cost articulated robots (cobots) is investigated. A sensor system is being developed to accurately determine the Tool Center Point (TCP) state of the robot, see Fig. 20.1, left. The processing of large-area components by mobile robot systems is also being investigated, see Fig. 20.1, right.

Higher-level issues, such as how data generated during prototype development and use can be used, are also part of the work. The question of under what circumstances the components produced by means of the prototypes can be compared with later series components is being investigated as part of the work.

Fig. 20.1 MVP of a Tool Center Point sensing unit (left), MVP of a mobile robotic system for laser material processing (right)

Among other things, the following questions, some of which are of a higher order, will be addressed in the project:

- How can data generated during prototype development and use be applied?
- Under what circumstances are the components produced by means of the prototypes comparable with later, series-produced components.

Furthermore, the integration of the prototypes into the data lake planned in the Internet of Production (IoP) is being pursued .

20.3.2 Automated Process Optimization for the Production of Individualized Sheet Metal Parts

Flexible manufacturing processes, such as 3D printing, enable rapid product development and highly individualized products. A promising process to manufacture individual sheet metal parts in small quantities is incremental sheet forming (ISF), which has high geometric flexibility due to low tool binding. The process combination with stretch forming enables overcoming known process limits and significantly reduces the process time. In the part shown in Fig. 20.2, the global part curvature has been achieved by stretch forming, and ISF has been used for forming the cavities and other part features (Taleb et al. 2011).

The combination of the two forming processes results in a more complicated process planning (Bambach et al. 2009; Schmitz et al. 2020). At the same time, however, short development times and costs must be ensured, which is an important factor in efficient prototype design, especially for small quantities. For this reason, the Institute for Metal Forming (IBF) at RWTH Aachen University has been working on the further development of the planning chain for the digital automation and optimization of the process combination of stretch forming and ISF as part of the Cluster of Excellence.

The first step in process planning is the analysis of the part to be produced. For this purpose, the part surface is transferred to the planning tool and converted into a suitable three-dimensional mesh within the tool. With the help of the mesh, it can be evaluated whether the part can be produced with this process combination.

Fig. 20.2 Exemplary application part (inspection door Airbus A320), produced with the process combination of stretch forming and incremental sheet forming

After the first evaluation of the part, the process parameters, boundary conditions, and tool paths suggested by the tool are then automatically prepared for subsequent finite element (FE) simulations and transferred to the FE software via an interface. LS-Dyna from Livermore Software Technology Corporation is used as the FE solver for the simulation of the automatically planned forming process. Based on the automatic planning and simulation chain, an autonomous optimization loop was established with the help of an interface to the optimization program LS-Opt.

The optimization model can change the originally defined orientation of the part as well as the tool paths depending on the simulation result. Metamodels are used to optimize the process simulation and their predictive capability is iteratively improved until the model can predict an optimal parameter combination.

The developed automated planning and optimization tool can optimize the individual steps of the process chain by coupling CAD/CAM software with an FE solver.

By optimizing with the help of metamodels, various process parameters can be flexibly tested and evaluated automatically by the planning tool with the help of FE models, without the need for time-consuming and cost-intensive experiments. The usually iterative experimental procedure to find process parameters that enable a successful manufacturing process is replaced by a more efficient iterative optimization within an FE environment. In this way, the best possible parameter selection can be determined directly without material expenditure, in order to then manufacture the parts using the process combination. The optimization is mostly automated and virtual. As part of the further development of the tool, the remaining manual steps (such as the transfer of the results of the optimization between the process steps) are also to be supported by a software solution and the expansion and validation of the planning tool for other geometries is to be advanced.

20.3.3 Toward an Agile Development of Laser Process Simulations Using Port-Hamiltonian Systems

Models of laser manufacturing processes live in different physical domains. The laser beam is an electromagnetic wave and, therefore, obeys Maxwell's equations. The beam can heat up a material, which is described by the heat equation.

High-temperature gradients occur during processing yield distortions, which is studied in solid mechanics. Hence, the analysis of laser manufacturing processes is a multi-physical endeavor. In addition, even small changes in the process, such as the switch from a sheet metal body to a plastic body in a car, can cause significant changes in the physical phenomena of, e.g., laser welding, which needs to be accounted for in a simulation. Finally, the laser manufacturing industry has already matured, and the trend goes toward the analysis of whole processes, e.g., the additive manufacturing process, instead of individual phenomena like laser-material interaction (Dahotre et al. 2022). To develop digital shadows and design tools, which predict desired properties of a prototype and hence enable an agile product development, it is therefore essential to account for the relevant multi-physical regimes and processes as well as material data.

In recent years, port-based modeling techniques from electrical engineering have been combined with Hamiltonian mechanics and concepts from differential geometry to form port-Hamiltonian systems (pHs) (van der Schaft and Jeltsema 2014). One of the key ideas underlying this modeling language is the separate description of energy-storing, energy-dissipating, and energy-routing elements as well as the definition of an interconnection structure, called (Stokes-) Dirac structure, which preserves power. Within the pHs framework, different physical phenomena can be described and analyzed separately from another. There is an ongoing effort to apply structure-preserving model reduction techniques to pHs to solve distributed parameter systems keeping the properties of the pHs, i.e., the power conservation and composability (Argus et al. 2021). In addition, a visual modeling language called bond-graphs exists, which is used to describe and reason about the simulations at an abstract level (Borutzky 2011). The interconnection properties of pHs enable the simulation of complex processes systematically composing simulations of elementary processes. This systematic approach also allows modifying or adding sub-models, which enables short development iterations and continuous feedback. Therefore, pHs have the potential to enable an agile product development tool with which one can interchange sub-models to more easily answer change requests that might require different physical phenomena to be included in a simulation. In addition, the ability to bring problems in input-state-output form can be used to integrate process data in, e.g., a control loop or to integrate machine learning techniques. The input-state-output form also allows the integration of simulations in a data pipeline as it consumes a data stream as input and produces another one as output.

The separation of concerns inherent in pHs modeling has been used to model the different physical phenomena occurring in a coupled thermo-elasticity problem (Brugnoli et al. 2021; Argus et al. 2021) separately (c.f. Fig. 20.3 top left and top right).

Coupling the pHs of the heat conduction and linear elasticity problems yields again a pHs which can be represented as another bond graph (see Fig. 20.3 bottom center).

To show the potential of pHs in laser process simulations the authors are going to apply this modeling technique to predict thermally induced distortions occurring

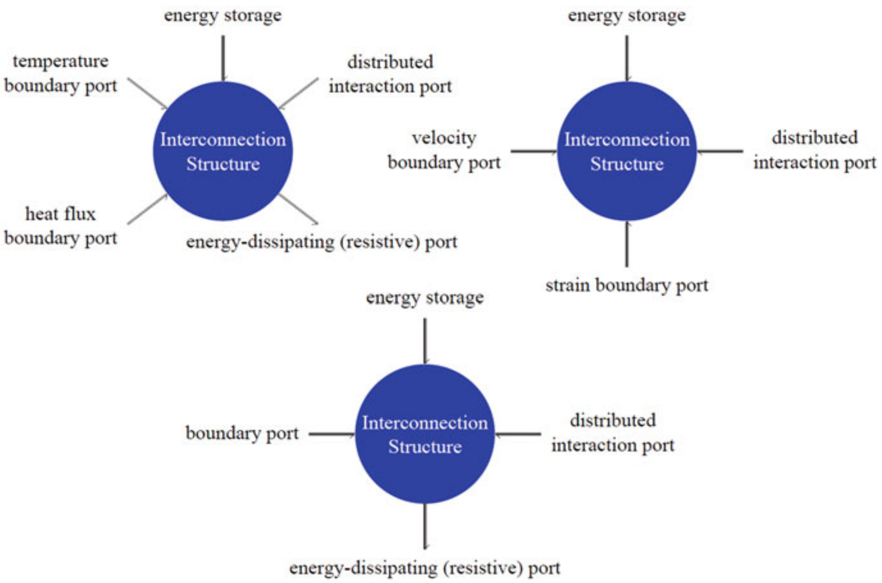


Fig. 20.3 The top left and top right bond graphs model a heat conduction, and a linear elastic structural mechanics problem, respectively. The combined bond graph is shown below

in laser additive manufacturing. The focus will be on the separate implementation of the sub-processes, and the interconnection of the reduced models at a later stage to form a co-simulation, which enables the use in design tools for additive manufacturing.

The pHs framework is a flexible approach to the mathematical modeling of multi-physical phenomena. It is used to study lumped and distributed parameter systems alike and, because of its interconnection properties, paves the way to develop co-simulations of complex systems or processes one step at a time.

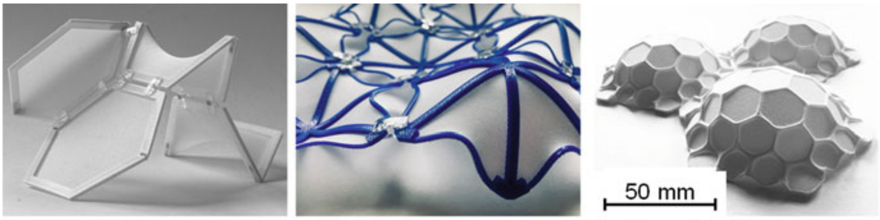
20.3.4 Modularity for 4D Textiles

The production of textiles is one of the oldest production techniques for products often worn close to the body. Recent developments focus on the creation of near net shape fabrics that allow for individualization on the one hand and conserving resources on the other hand. The process of three-dimensional printing, creating 3D structures by adding layer by layer of material, goes along with these requirements. The process of 3D printing with plastics was further developed into four-dimensional (4D) printing. In 4D printing, material structures are produced that can change their properties over time in a targeted manner. The fourth dimension describes the time in which a change in properties might occur after 3D printing, introduced by the influence of an external stimulus. The energy for the change of property is stored in the material and/or is introduced by the stimulus (Tibbits 2017).

Building on the principle of 4D printing, 4D textiles are textiles that can change shape or function over time by the influence of a stimulus, mainly force and heat. The shape change properties can be introduced in all textile production steps, such as fiber and fabric production and finishing (Pei et al. 2015). 4D textiles produced by 3D printing on prestressed textile (usually warp or weft knitted with elastic material) shape change from a 2,5D structure to a 3D structure resulting in bistable structures and hybrid systems of a minimum of two materials. By prestressing the textile, energy is brought in by using both the structural and material-based elasticity of the fabric. The prestressed textile is brought in as the new build surface. By printing beams on the fabric, the reset can be programmed thus resulting in defined 3D shapes (Koch et al. 2021).

Mainly fused filament fabrication (FFF) with thermoplastic materials such as PLA, TPU, or ABS is usually used. Tessellation techniques are used to design the printing patterns (Koch et al. 2021). Only few approaches exist that model aspects of the behavior of 4D textiles. Kycia and Guiducci present an approach to model lines (Kycia and Guiducci 2020), Perèz et al. model Kirchhoffsche plateau principles to design complex interaction principles (Pérez et al. 2017). 4D textiles have proven to allow rapid prototyping of complex shapes and prototypes. As a design method, Schmelzeisen et al. proposed an adapted Design Thinking approach to integrate both the need-finding and the technical definition process in one (Schmelzeisen et al. 2018). The current process results in a variety of models and applications. Models rarely build on each other thus knowledge must be generated for every new model (Fig. 20.4).

To enable the development of MVPs, 4D textiles are defined as propagating structures, a concept derived from nature. These structures are open and entangled which enable them to be resilient and adaptable. Building on this, 4D textiles are digital materials that consist of a discrete set of parts (modules), which are reversibly joined (Popescu et al. 2006). Each module performs a function and is linked to other modules along the edge to build a system. An input at one point of the systems can turn the whole system into something completely different with a different function. For validation, three basic modules have been designed and the concept of propagation using user interaction with these modules and simple joints has been tested. The modules represent three core properties of the material:



Self folding Self bending Self contracting

Fig. 20.4 Basic modules of 4D printing on textiles: Self-folding, self-bending, and self-contracting

Self-contracting, self-bending, and self-folding. The combination of modules with joints allows for complex structures. Modularity as design approach for MVPs thus for agile product development has a high potential for three reasons: the complexity to describe separated modules decreases, standardization of the modules helps to bring them as objects in the product design process (e.g., CAD) and scaling principles from micro to nano level. The modular design allows to build complex systems of basic modules for different application fields. Huge potential lies in architecture, medicine, interactive surfaces, and robotics.

20.3.5 Functionality for Free – Paving the Way for Multi-Material Additive Manufacturing

Fused filament fabrication (FFF)) is an established additive manufacturing (AM) process for prototyping of thermoplastic components. Its popularity is based on inexpensive equipment, high usability, and accessible process control (Osswald 2017). Many FFF processes are suitable to process two different colors or materials subsequently. A second material is mostly used for support structures, and interlayer adhesion between different materials is often weak. Due to its manner of adding material locally, one major advantage of AM is the ability to change material composition and density within a component. By intentionally varying applied materials and thereby integrating multiple functionalities in a single component, tremendous potential for agile prototyping is unlocked. This technology enables the evolution from a contour-dependent design approach to a material-centric, performance-driven design approach (Loh et al. 2018). Starting from the initial idea, the final product can be conceptualized by focusing on the material and its distribution rather than having manufacturing or design constraints shape the final morphology. Employing agile principles, this allows a rapid response to design and requirement changes as the material can be adapted in its composition and thus its function in a single-step process. Therefore, the time from idea to prototype and finally the product shortens significantly. Single components can substitute assemblies and users are able to reduce the dependency on suppliers for off-the-shelf equipment of small products. A low degree of adhesion between multiple materials in FFF, however, limits the range of possible applications and displayable functionality.

This research aims to understand and improve the process of multi-material FFF to support prototyping within the scope of agile product development. Smooth transitions between different materials can be generated by employing a nozzle design that combines two feedstock materials and deposits them in a single bead. Adhesion is expected to improve as opposed to distinct and subsequent material extrusion due to molecular processes that are initiated by pressure and temperature within the nozzle, as well as macroscopic mechanical interlocking within the prototype (Kennedy and Christ 2020; Khondoker et al. 2018). Moreover, compositional changes during printing allow for the creation of so-called functionally graded materials (FGM) whose properties can be tuned spatially. FGMs are known from nature where a graded structural transition allows for, e.g., optimized load transfer in bones or wood (Oxman 2011).

Identified use-cases for components by functionally graded multi-material additive manufacturing (FGAM) spread from e-mobility to an integrated Internet of Production. Within e-mobility, graded reinforcement can support the design and production of lightweight structural components. Within the Internet of Production, conductive gradients within components may support failure monitoring: By continuously measuring conductivity of abrasion-loaded manufacturing tools, existing machinery may be digitalized without the need for larger investments.

Experiments are conducted with a modified FFF desktop machine. The two materials are jointly molten and deposited by a single nozzle. The modification of common g-codes by a parser allows the continuous adjustment of the ratio of extruded material according to a previously determined gradient. During the built-up, process data is continuously measured. A hotspot allows the data transfer between printer and an exchangeable computer. Data records shall be analyzed to indicate both building progress and potential failure. General knowledge shall be extracted to be applicable for any subsequent and unique prototyping process.

Holistic experiments have been conducted for the combination of a brittle polylactide acid (PLA) and a ductile thermoplastic polyurethane (TPU) with the possibility of changing the composition in the process. Statistical analysis of the samples demonstrates a profound relationship between the content of TPU and properties like the elastic modulus, tensile strength, and correlated strain. Specimen's properties depend on design features like the composition ratio or the course of the gradient as well as on process parameters like temperature profiles.

Two main challenges remain within the process: First, material selection requires careful consideration, since the separation of jointly processed FGMs of dissimilar materials is difficult. A possible solution may be the combination of a compostable and a recyclable material. The combination of a virgin material with a secondary material might increase the usability of pre-used materials of lower quality but limits the integration of advanced functionality compared to the use of dissimilar materials. Second, the complexity for designers in FGAM increases drastically due to adding the dimension of material composition. An intuitive and predictive software to support users with the spatial assignment of macroscopic and microscopic material properties is required (Gebhardt et al. 2019). Only by ensuring predictability of part performance of a heterogeneous component with compositional material changes, FGAM will be suitable for advanced prototyping in different industries.

20.3.6 A Tool for Algorithmic Generation of Lattice Structures for Additive Manufacturing

Lattice structures are lightweight constructions which have specific characteristics, such as high surface area to volume ratio and excellent strength to weight ratio (Savio et al. 2018). Additive manufacturing (AM) technologies for the processing of metals, specifically laser powder bed fusion (LPBF), enable the fabrication of such complex structures. However, there exist challenges with the generation, data pre-processing, data handling, and simulation of AM-compliant lattice structures. The lattice structures created by most of the CAD software products are usually non-conformal, and they usually do not consider AM-specific producibility constraints such as minimum allowed distance between CAD features or threshold overhang angle which could result in failure of the AM fabrication of lattice structures. Furthermore, working with volumetric CAD data for the creation and pre-processing of lattices is usually difficult and non-real-time, and the generation process may fail when working on CAD data generated by another software. Moreover, the simulation of lattice structures is challenging due to a large number of mesh elements (Dong et al. 2017).

To address these issues, an algorithmic approach for the generation of lattice structures is introduced in which the AM producibility constraints are respected. This requires creation of a database including producibility data for each AM production machine and material. Furthermore, algorithms for the generation of AM-compliant conformal lattices are developed; the stiffness and strength of conformal lattice structures could be higher than trimmed lattices (Liang et al. 2018). To analyze and improve the behavior of lattice structures under mechanical loading, they are simulated and optimized. The simulation approaches aiming at the reduction of mesh elements while predicting the behavior with high accuracy are also developed and linked to the lattice generation tool, as depicted in Fig. 20.5.

The developed tool can automatically create lattice structures which conform to AM production constraints and then locally adapt the meshing techniques to ensure finer meshes at strut joints. Cubic/cuboid use cases with an f_2cc, z unit cell of a size of $3 \times 3 \times 3$ mm^3 were meshed adaptively and simulated under mechanical loading

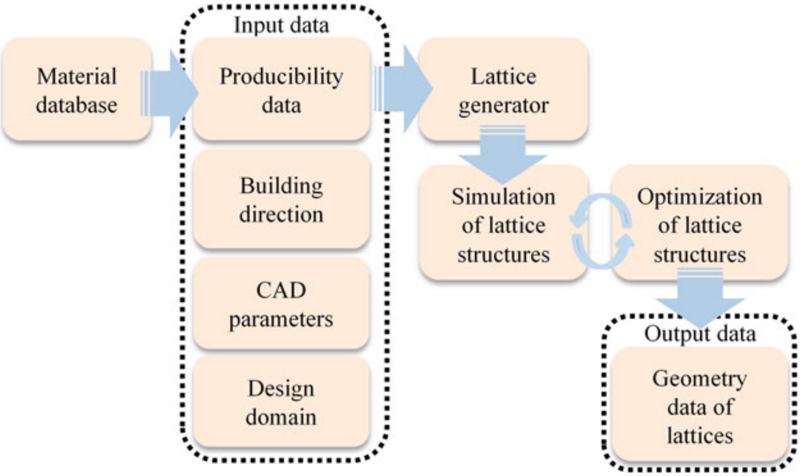


Fig. 20.5 The framework for the algorithmic generation and optimization of lattice structures

in the elastic regime, and they produced comparable results with that of uniform meshing with a difference below 1% while reducing the number of elements per unit cell by approx. 70%.

The developed tool should be further equipped with algorithms for the creation of lattice structures for arbitrary freeform design spaces. In addition, the simulation approaches should be further enhanced for lattice structures with a larger number of mesh elements. For the optimization of lattice structures, refinement algorithms and/or size optimization methods should be implemented. The created tool enables agile product development of lightweight efficient structures by quick adaptation of the design in response to the requirements of the material, load and boundary conditions, and customer demands such as the topology and geometry of lattice structures. Furthermore, the tool handles the data in a smart manner by generation, simulation, and optimization of the structures in one platform to eliminate or remarkably reduce the involved challenges with lattice processing. The created lattice structures could be used in biomedical, heat transfer, hydrogen storage and vibration control applications (Du Plessis et al. 2022) as well as in heterogeneous catalysis. The data acquired from simulations can be stored as a part of the digital twin of lattices and can be used for optimization purposes.

20.3.7 Agile Alloy Development for Metal Additive Manufacturing

During the last years, the field of additive manufacturing (AM) of metals has witnessed the rise of data-driven approaches as an enabler for agile product development. Numerous examples of data-driven approaches can be found in component design (Oh et al. 2019), in quality control (Tian et al. 2021), and defect detection (Scime and Beuth 2018). So far, the development of new alloys for metal AM depends on time-consuming experiments and simulations to understand process-microstructure-property (PSP) linkages and requires high computational costs. We propose a framework (Fig. 20.6) that provides python-based tools for an efficient description of linkages between additive manufacturing process, microstructure, and mechanical response of metals for AM. The framework contains different strategies to differentiate cases of different complexity level (e.g., low-complexity morphology-dominated and high-complexity morphology- and texture-dominated microstructures).

The results in Fig. 20.7 present an example for building a relationship between process parameters based on physics-based kinetics Monte Carlo (kMC) simulations and the corresponding microstructural feature in terms of the directional chord length distribution (CLD). Directional CLDs capture the morphological characteristics in 3D of AM microstructures. Further data compression by principal component analysis (PCA) reduces the data space for building efficient relationships by ML-based regression algorithms. Regression models substitute computational expensive kMC simulations for new queries on the process parameters of interest. The framework will be extended by an invertible neural network to get direct predictions on the design space (e.g., chemical composition, laser speed, etc.), since typically

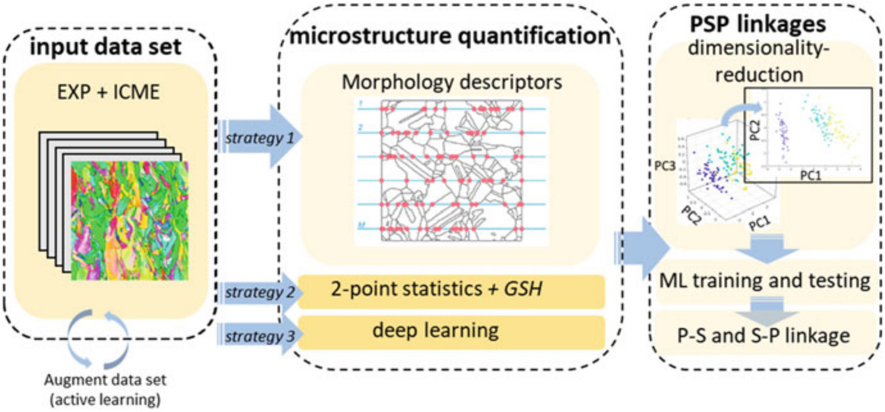


Fig. 20.6 Data-driven/ML framework to establish Process-(micro)Structure (P-S) and (micro)Structure-Property (S-P) linkages (forward-propagation) as the basis to find inverse solutions for an optimized AM design space

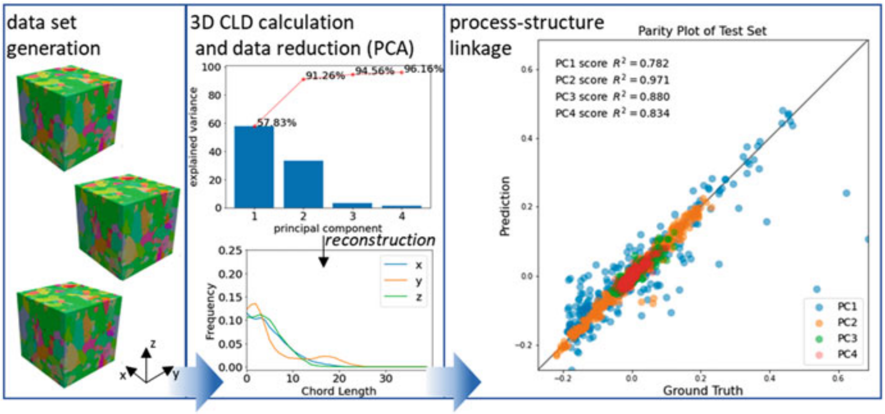


Fig. 20.7 Revealing the P-S linkage during AM derived from 3D microstructures using a data-driven framework. Applied 3D chord length distributions (in x-y-z directions) of the microstructures reduced by PCA represent input data for the model. The P-S relationships are predicted by ML-based regression as output. In total 960 represented volume elements (RVE) simulated with a SPPARKS kMC subroutine (modified Potts-Monte Carlo model (Rodgers et al. 2017)) account for the used input data

the development of new alloys requires answers to inverse-directed questions (e.g., what is the process parameter space to reach a certain deformability?). In summary, the framework enables fast and computational efficient predictions along the P-S-P chain.

20.3.8 Optical Systems Development

For various applications in laser material processing, such as laser welding, polishing, or engraving, individual optical systems are required depending on the laser source and desired beam characteristics. The optics design is a time-consuming process and depending on the complexity of the system experts need up to several weeks or months for designing, analyzing, and tolerancing. For many custom designs the employed lenses must be individually manufactured, which is expensive. This can be circumvented by adaption of the optics design for the use of low-cost stock lenses. For agile product development, the time and cost factor for an individual lens manufacturing is not sustainable.

To make the design of optical systems accessible for agile product development, an application is developed which automatically designs optical systems from stock components, which are available quickly and at low costs. These optical systems are used for the first prototype application and are continuously improved during the agile development circle. In the first prototyping step, as a demonstrator a three-lens system is considered.

The design of a three-lens system is realized by computing all possible combinations of commercially available stock lenses from a given catalog (König 2021; König et al. 2021). In order to avoid a calculation time that increases cubically with the number of stock lenses and to minimize the amount of time-consuming exact ray-tracing calculations, clustering methods of the configuration space as well as simplifications of the optical propagation (the so-called paraxial raytracing) are used. A subsequent automated tolerance analysis (König et al. 2017) against assembly deviations allows the design of robust optical systems such as the plane-field optics shown in Fig. 20.8.

For agile product development, continuous adjustments of the optical design are necessary to meet the changing requirements of the stakeholders. The three-lens

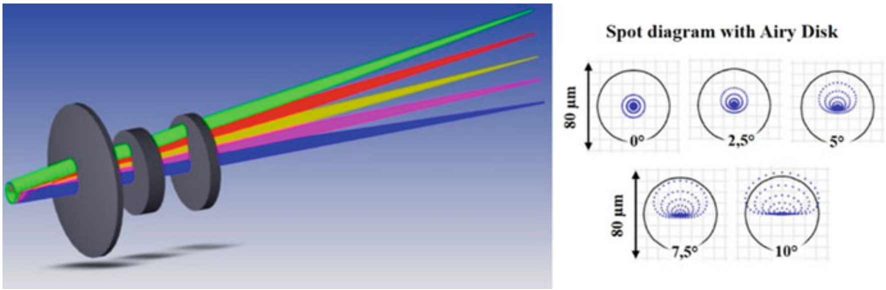


Fig. 20.8 Exemplary design – Plane-field optics with 6 mm laser beam diameter, 150 mm focal length, 10° field angle, and 1064 nm wavelength. The system is smaller than 50 mm in the length. The incident rays on the image plane are within the airy disk, which describes the maximal physical focusability for an optical system

system must therefore be adapted, improved, and finalized to the new requirements. This usually results in optical systems with a large number of lenses.

To carry out these adaptations, the next step is the development of a method based on artificial intelligence (AI) for automated optics design (Fu et al. 2021, 2022). Utilizing reinforcement learning an agent has to be trained to set up and optimize an optical system. The agent automatically adapts an existing prototype (start system) to find a design matching the new requirements of the stakeholders. This can be done within few minutes to reduce the latency time in the agile product development.

20.4 Conclusion

In this chapter, the development of enabling technologies and interactive tools for an agile product development in the context of the Internet of Production (IoP) is presented. For this purpose, the state of the art of agile product development is described as an introduction. Building on this, advanced manufacturing technologies (AMTs) are presented as enablers and tools in the context of agile product development. Here, the possible uses of AMTs as manufacturing processes for prototypes are further developed. For each AMT, usage and integration of the technology and data acquired during manufacturing in agile development environments is explored. Also, the use of relevant data from production and material to determine the minimum viability of a product prototype as well as to select, adapt, and improve the respective prototyping technologies is investigated.

Acknowledgments Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC–2023 Internet of Production – 390621612.

References

Argus FJ, Bradley CP, Hunter PJ (2021) Theory and implementation of coupled port-Hamiltonian continuum and lumped parameter models. J Elast:339–382. https://doi.org/10.1007/s10659-021-09846-4

Bambach M, Taleb AB, Hirt G (2009) Strategies to improve the geometric accuracy in asymmetric single point incremental forming. Prod Eng Res Dev:145–156. https://doi.org/10.1007/s11740-009-0150-8

Baumers M, Dickens P, Tuck C, Hague R (2016) The cost of additive manufacturing: machine productivity, economies of scale and technology-push. Technol Forecast Soc Chang 102:193–201. https://doi.org/10.1016/j.techfore.2015.02.015

Behera AK, Verbert J, Lauwers B, Duflou JR (2013) Tool path compensation strategies for single point incremental sheet forming using multivariate adaptive regression splines. Comput Aided Des 45:575–590. https://doi.org/10.1016/j.cad.2012.10.045

BMBF (2018) Forschung und Innovation für die Menschen. Die Hightech-Strategie 2025. Edited by Bundesministerium für Bildung und Forschung (BMBF), Referat Grundsatzfragen der Innovationspolitik, checked on 2/8/2022

Borutzky W (ed) (2011) Bond graph modelling of engineering systems: theory, applications and software support. Springer

Brecher C, Özdemir D, Weber AR (2017) Integrative production technology – theory and applications. In: Brecher C, Özdemir D (eds) Integrative production technology: theory and applications. Springer, Cham, pp 1–17

Brugnoli A, Alazard D, Pommier-Budinger V, Matignon D (2021) A port-Hamiltonian formulation of linear thermoelasticity and its mixed finite element discretization. J Ther Stress 44:643–661. https://doi.org/10.1080/01495739.2021.1917322

Cen L, Melkote SN, Castle J, Appelman H (2016) A wireless force-sensing and model-based approach for enhancement of machining accuracy in robotic milling. IEEE/ASME Trans Mechatron 21:2227–2235. https://doi.org/10.1109/TMECH.2016.2567319

Cochard J, d'Humières B (2019) Der globale Mindestbeitrag der Photonik zum Klimaschutz anhand ausgewählter Beispiele: 3 Milliarden Tonnen weniger CO2. In: Messe München GmbH, SPECTARIS (eds) Licht als Schlüssel zur globalen ökologischen Nachhaltigkeit

Dahotre NB, Pantawane MV, Sharma S (2022) Laser-based additive manufacturing modeling, simulation and experiments. Wiley-VCH

Dong G, Tang Y, Zhao Y (2017) Simulation of elastic properties of solid-lattice hybrid structures fabricated by additive manufacturing. Proc Manuf 10:760–770. https://doi.org/10.1016/j.promfg.2017.07.072

Du Plessis A, Razavi SMJ, Benedetti M, Murchio S, Leary M, Watson M, Bhate D, Berto F (2022) Properties and applications of additively manufactured metallic cellular materials: a review. Prog Mater Sci 125:100918. https://doi.org/10.1016/j.pmatsci.2021.100918

Fu C, Stollenwerk J, Holly C (2021) Lens bending with reinforcement learning for reduced optical aberrations. In: Frontiers in optics + laser science 2021. OSA, Washington, DC

Fu C, Stollenwerk J, Holly C (2022) Reinforcement learning for guiding optimization processes in optical design. Proc. SPIE 12227, Applications of Machine Learning 2022, 1222709. https://doi.org/10.1117/12.2632425

Gebhardt A, Kessler J, Schwarz A (2019) Produktgestaltung für die Additive Fertigung. Hanser; Ciando, München

Goll J (2015) Mit Scrum zum gewünschten System. Springer eBook Collection. Springer Vieweg, Wiesbaden

Highsmith J, Fowler M (2001) The agile manifesto. Softw Dev Mag 9:29–30

Hinke C (2018) Digitale photonische Produktion. Dissertation, RWTH Aachen University

Hügel H (2009) Laser in der Fertigung: Strahlquellen, Systeme, Fertigungsverfahren, 2nd edn. SpringerLink Bücher, Wiesbaden

Kantelberg J (2018) Gestaltung agiler Entwicklungsprozesse technischer Produkte. Dissertation, RWTH Aachen University

Kennedy ZC, Christ JF (2020) Printing polymer blends through in situ active mixing during fused filament fabrication. Addit Manuf. https://doi.org/10.1016/j.addma.2020.101233

Khondoker MAH, Asad A, Sameoto D (2018) Printing with mechanically interlocked extrudates using a custom bi-extruder for fused deposition modelling. Rapid Prototyp J. https://doi.org/10.1108/RPJ-03-2017-0046

Klein T (2016) Agiles Engineering im Maschinen- und Anlagenbau. Dissertation

Koch HC, Schmelzeisen D, Gries T (2021) 4D textiles made by additive manufacturing on pre-stressed textiles – an overview. Actuators 10:31. https://doi.org/10.3390/act10020031

König H-GM (2021) Automated design of optical systems made of stock lenses. RWTH Aachen University

König G, Chen C-W, Holters M, Stollenwerk J, Loosen P (2017) Comparison of different methods for robustness estimation of simple lens systems. In: Pfisterer RN, Rogers JR, Muschaweck JA, Clark PP (eds) International optical design conference 2017. SPIE, p 32

König G, Fu C, Stollenwerk J, Holly C, Loosen P (2021) Automated lens design for optical systems consisting of stock lenses. Opt Express 29:39027–39041. https://doi.org/10.1364/OE.442176

Kycia A, Guiducci L (2020) Self-shaping textiles: a material platform for digitally designed, material-informed surface elements. In: Werner LC, Köring D (eds) Anthropologic – architecture and fabrication in the cognitive age, 1st edn. eCAADe, Brussels

Liang Y, Yoo D, Han H (2018) An effective geometric modeling method for 3D lattice structures using volumetric distance field. JEMM 3. https://doi.org/10.23977/jemm.2018.31004

Loh GH, Pei E, Harrison D, Monzón MD (2018) An overview of functionally graded additive manufacturing. Addit Manuf 23:34–44. https://doi.org/10.1016/j.addma.2018.06.023

Oh S, Jung Y, Kim S, Lee I, Kang N (2019) Deep generative design: integration of topology optimization and generative models. J Mech Des 141:436. https://doi.org/10.1115/1.4044229

Osswald TA (2017) Understanding polymer processing: processes and governing equations, 2nd edn. Hanser Publishers, Munich/Cincinnati

Oxman N (2011) Variable property rapid prototyping. Virtual Phys Prototyp 6:3–31. https://doi.org/10.1080/17452759.2011.558588

Panesar A, Abdi M, Hickman D, Ashcroft I (2018) Strategies for functionally graded lattice structures derived using topology optimisation for Additive Manufacturing. Addit Manuf 19:81–94. https://doi.org/10.1016/j.addma.2017.11.008

Pei E, Shen J, Watling J (2015) Direct 3D printing of polymers onto textiles: experimental studies and applications. Rapid Prototyp J 21:556–571. https://doi.org/10.1108/RPJ-09-2014-0126

Pérez J, Otaduy MA, Thomaszewski B (2017) Computational design and automated fabrication of kirchhoff-plateau surfaces. ACM Trans Graph 36:1–12. https://doi.org/10.1145/3072959.3073695

Popescu GA, Kunzler P, Gershenfeld N (2006) Digital printing of digital materials. In: Digital fabrication 2006 final program and proceedings, Society for Imaging Science and Technology, Denver, pp 55–57

Poprawe R (2005) Lasertechnik für die Fertigung: Grundlagen, Perspektiven und Beispiele für den innovativen Ingenieur. SpringerLink Bücher. Springer Berlin Heidelberg, Berlin/Heidelberg

Poprawe R (2019) Photonik als “Enabler” für den Klima- und Umweltschutz. In: Messe München GmbH, SPECTARIS (eds) Licht als Schlüssel zur globalen ökologischen Nachhaltigkeit. Hightech-Lösungen der Photonik für den Schutz von Umweld und Ressourcen, Berlin/München, pp 12–17

Rodgers TM, Madison JD, Tikare V (2017) Simulation of metal additive manufacturing microstructures using kinetic Monte Carlo. Comput Mater Sci 135:78–89. https://doi.org/10.1016/j.commatsci.2017.03.053

Savio G, Rosso S, Meneghello R, Concheri G (2018) Geometric modeling of cellular materials for additive manufacturing in biomedical field: a review. Appl Bionics Biomech 2018:1654782. https://doi.org/10.1155/2018/1654782

Schmelzeisen D, Koch H, Pastore C, Gries T (2018) 4D textiles: hybrid textile structures that can change structural form with time by 3D printing. In: Kyosev Y, Mahltig B, Schwarz-Pfeiffer A (eds) Narrow and smart textiles. Springer, Cham, pp 189–201

Schmitz RUC, Bremen T, Bailly DB, Hirt G (2020) On the influence of the tool path and intrusion depth on the geometrical accuracy in incremental sheet forming. Metals 10:661. https://doi.org/10.3390/met10050661

Schuh G (2017) Agile Produktentwicklung. In: Brecher C, Klocke F, Schmitt R, Schuh G (eds) Internet of production für agile Unternehmen, 1st edn. Apprimus Verlag, Aachen

Schuh G, Haller C, Lindner N, Spangler T, Walch M, van Dijk L, Lau F, Kantelberg JE (2017) Radikale Innovation und neue Geschäftsmodelle. In: Brecher C, Klocke F, Schmitt R, Schuh G (eds) Internet of Production für agile Unternehmen, 1st edn. Apprimus Verlag, Aachen, pp 109–131

Scime L, Beuth J (2018) A multi-scale convolutional neural network for autonomous anomaly detection and classification in a laser powder bed fusion additive manufacturing process. Addit Manuf 24:273–286. https://doi.org/10.1016/j.addma.2018.09.034

Sommerville I (2010) Software engineering, 9th edn. Pearson, Boston/Munich

Statistisches Bundesamt (2022) Volkswirtschaftliche Gesamtrechnungen. Inlandsproduktberechnung Vierteljahresergebnisse - 4. Vierteljahr 2021. Fachserie 18 Reihe 1.2. Edited by Statistisches Bundesamt (Destatis). Statistisches Bundesamt (Destatis). Available online at https://www.destatis.de/DE/Themen/Wirtschaft/Volkswirtschaftliche-Gesamtrechnungen-Inlandsprodukt/Publikationen/Downloads-Inlandsprodukt/inlandsprodukt-vierteljahr-pdf-2180120.pdf?__blob=publicationFile, checked on 4/20/2022

Taleb B, Göttmann A, Bambach M, Hirt G (2011) Review on the development of a hybrid incremental sheet forming system for small batch sizes and individualized production. Prod Eng 5:393–404. https://doi.org/10.1007/s11740-011-0325-y

Tian Q, Guo S, Melder E, Bian L, Guo WG (2021) Deep learning-based data fusion method for in situ porosity detection in laser-based additive manufacturing. J Manuf Sci Eng 143. https://doi.org/10.1115/1.4048957

Tibbits S (2017) Skylar tibbits: the emergence of “4D printing”. https://www.ted.com/talks/skylar_tibbits_the_emergence_of_4d_printing. Accessed 29 Mar 2022

van der Schaft A, Jeltsema D (2014) Port-Hamiltonian systems theory: an introductory overview, Foundations and Trends in Systems and Control: Vol. 1(2-3): 173–378. https://doi.org/10.1561/2600000002

Wu D, Rosen DW, Wang L, Schaefer D (2015) Cloud-based design and manufacturing: a new paradigm in digital manufacturing and design innovation. Comput Aided Des 59:1–14. https://doi.org/10.1016/j.cad.2014.07.006

Zaeh MF, Ott M (2011) Investigations on heat regulation of additive manufacturing processes for metal structures. CIRP Ann 60:259–262. https://doi.org/10.1016/j.cirp.2011.03.109