

Scalable Production Infrastructure for Extrusion-based Additive Manufacturing of Personalized Medical Scaffolds

Skalierbare Produktionsinfrastruktur für die Extrusionsbasierte Additive Fertigung Personalisierter Medizinischer Scaffolds

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Zusammenfassung

Personalisierte Medizinprodukte gewinnen zunehmend an Bedeutung, insbesondere im Bereich der regenerativen Medizin. Einen Teil dieser Entwicklung repräsentieren bioresorbierbare Scaffolds, die an die individuellen Geometrien der Patientinnen und Patienten angepasst werden und für die Rekonstruktion von Geweben und Organen zum Einsatz kommen. Für diese dreidimensionalen Gerüststrukturen ist der extrusionsbasierte 3D-Druck eine der etabliertesten Fertigungstechnologien. Der Stand der Technik zeigt, dass wesentliche Prozessschritte, wie die Parametrisierung des Druckers, das Materialhandling, die Drucküberwachung sowie die Inspektion der fertigen Produkte und dessen Qualitätsbewertung manuell durchgeführt werden. Dieses Vorgehen ist nur unter hohem Personaleinsatz skalierbar und limitiert die Produktionseffizienz. Da die gesamte Herstellung medizinischer Scaffolds in einer kontrollierten, regularienkonformen Reinraumumgebung stattfinden muss, stellt der Mensch als Teil der Produktionskette ein Risiko für Kontamination und Fehler dar, was die Vorteile einer automatisierten Lösung betont. Die Gestaltung einer entsprechenden automatisierten Produktionsinfrastruktur für die Fertigung personalisierter Scaffolds, wurde als Forschungslücke identifiziert und bildet das Ziel der Arbeit. Dies wird sowohl konzeptionell als auch mittels physischer Demonstratoren und digitaler Modelle untersucht.

Das zentrale Ergebnis der Arbeit ist ein Konzept für eine neuartige Produktionsinfrastruktur, die auf einem magnetischen Planarantrieb basiert. Dieser Antrieb wird zum einen für die Produktionsintra-logistik eingesetzt und ermöglicht durch einen Multi-Agenten-Ansatz eine Flexibilisierung und Simultanisierung mehrerer Druckaufträge im Sinne der freiverketteten Produktion. Zum anderen werden die einzelnen Agenten des Planarantriebs, die sogenannten Mover, als Druckbett und horizontale Kinematik für den 3D-Druck verwendet, sodass sich die Druckprozesse der einzelnen Schichten, die Intra-logistik und andere Prozessschritte, wie Qualitätskontrollen, nahtlos miteinander verbinden lassen. Zur Validierung dieser Ansätze wurde ein Demonstrator entwickelt, der für Machbarkeitsstudien zum Einsatz kam. Parallel dazu wurde ein digitales Abbild der Produktionsinfrastruktur erstellt, welches in einer ereignisdiskreten Simulationsumgebung implementiert wurde. Es konnte gezeigt werden, dass das digitale Modell die Prozessabläufe des physischen Demonstrators realistisch nachbilden kann. Darüber hinaus wurde anhand von Simulationsstudien nachgewiesen, dass das Modell zur Skalierungsplanung der Produktion genutzt werden kann. Ebenso wurde simulativ die Verwendbarkeit des Modells zur Optimierung der Produktionsprozesse untersucht. Diese Optimierungen betreffen beispielsweise die Gestaltung des Layouts der Produktionsplattform, inklusive der Anordnung einzelner Stationen, oder die Optimierung technischer Parameter wie Prozess- und Transportgeschwindigkeiten. Die Untersuchungen zeigen, dass das entwickelte Konzept nicht nur für die Produktion personalisierter medizinischer Scaffolds geeignet ist, sondern auch das Potenzial bietet, auf andere Anwendungen übertragen zu werden.

Summary

Personalized medical products are becoming increasingly important, especially in the field of regenerative medicine. Part of this development is represented by bioresorbable scaffolds, which are adapted to the individual geometries of patients and used for the reconstruction of tissues and organs. Extrusion-based 3D printing is one of the most established manufacturing technologies for these three-dimensional scaffold structures. The state of the art shows that essential process steps, such as printer parameterization, material handling, print monitoring, and inspections of the finished products and their quality assessment, are performed manually. These approaches are difficult to scale and limit the efficiency of the production. Since the entire production of medical scaffolds must take place in a controlled, regulatory-compliant cleanroom environment, humans involved in the production chain pose a risk of contamination and error, which highlights the advantages of an automated solution. The design of an appropriate automated production infrastructure for the manufacture of personalized scaffolds has been identified as a research gap and is the objective of this work. The topic is being investigated conceptually and by utilizing physical demonstration systems and digital models.

Central result of the work is a concept for a novel production infrastructure based on a magnetic planar drive system. This planar drive is used for production intralogistics and enables a multi-agent approach for flexibilization and simultaneous processing of multiple print jobs in the sense of decoupled production. On the other hand, the individual agents of the planar drive, referred to as movers, are used as print beds and the horizontal kinematics for 3D printing, allowing the printing processes of the individual layers, intralogistics, and other process steps, such as quality control, to be seamlessly connected. To validate these approaches, a demonstrator was developed and used for feasibility studies. In parallel, a digital representation of the production infrastructure was created and implemented in an event-discrete simulation environment. It was demonstrated that the digital model can realistically replicate the decoupled process flows of the physical demonstrator. Furthermore, simulation studies proved that the model can be used for planning the scale-up of the production. The usability of the model for optimizing production processes was also investigated in simulation studies. These optimizations relate to the design of the production platform layout, including the arrangement of individual stations or the optimization of technical parameters such as process and transport speeds. The investigations show that the developed concept is not only suitable for the production of personalized medical scaffolds but also has the potential to be transferred to other applications.

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1 Introduction

Technological advancements and innovative approaches in medical technology enable a continuous improvement of healthcare. Personalized medicine is gaining increasing significance. Patient-specific medical products, such as implants or custom-designed tools tailored to the unique anatomy of individual patients, exemplify this trend. The personalized knee implant is one of the most prominent and well-established applications (Murr, 2020). It has been demonstrated that the customization of medical products offers benefits for both patients and the healthcare system. On one hand, it reduces operation time and costs (O'Connor and Blau, 2019), while on the other hand, it enhances patient recovery and satisfaction with surgical interventions (Schroeder et al., 2022). Currently, there is an increasing establishment of polymer-based applications for personalized medical implants, such as bioresorbable scaffold structures for regenerating bone or soft tissue (Backes et al., 2022; Xu and Ivanovski, 2025).

Additive manufacturing has proven to be a suitable method for producing polymer-based personalized scaffolds for research and healthcare applications. Extrusion additive manufacturing (EAM) techniques have demonstrated their effectiveness due to low costs and high adaptability (Oleksy et al., 2023). The flexibility to utilize biocompatible printing materials and the seeding of human cells into products are empowering further innovative therapeutic approaches, which are referred to as tissue engineering. Despite the promising benefits, the current production landscape for personalized printed medical scaffolds is at a rudimentary stage. Manufacturing processes are often characterized by a lack of automation and rely heavily on manual interventions (Ali et al., 2025). Labor-intensive tasks such as material supply, quality control and handling of products are performed by skilled personnel in cleanroom environments, complicating the scaling of production throughput (Parulski et al., 2021). Only a few use cases are known where automated production infrastructures for the manufacture of medical scaffolds are established, and none of them addresses specifically the EAM process or is able to automate the holistic production of personalized, lot-size-one scaffolds (Formlabs, 2024; Ng et al., 2024; Nycz et al., 2018).

Growing markets for personalized regenerative medicine and the associated production of individual medical products necessitate that the corresponding production technologies allow for a higher degree of customization while maintaining efficiency and safety (Fairfield Market Research, 2024; Pathak et al., 2023). Medical products operate within a regulated domain, which complicates the design of the production environment. At the same time, scalable and automated manufacturing is required to be considered for widespread and cost-effective use in healthcare delivery. An established tool in other industries for planning the scaling and optimization of a production is the use of digital models to simulate production lines or entire infrastructures (Müller et al., 2019). Digital models are also indispensable in quality management (QM) for the transition from reactive to predictive QM (Asif, 2020; Silva et al., 2024). Production in the context of personalized medicine is lagging behind this trend, which forms a current research and development demand (Parulski et al., 2021).

1.1 Initial Situation and Motivation

This work addresses the product category of personalized 3D-printed medical products, as shown in Figure 1. This can be further subdivided into the groups of orthoses and prostheses (1-3), implants (4-9), and surgical equipment and training models (10-11). Annex A.1 provides a literature overview for the individual products with their specific medical applications.

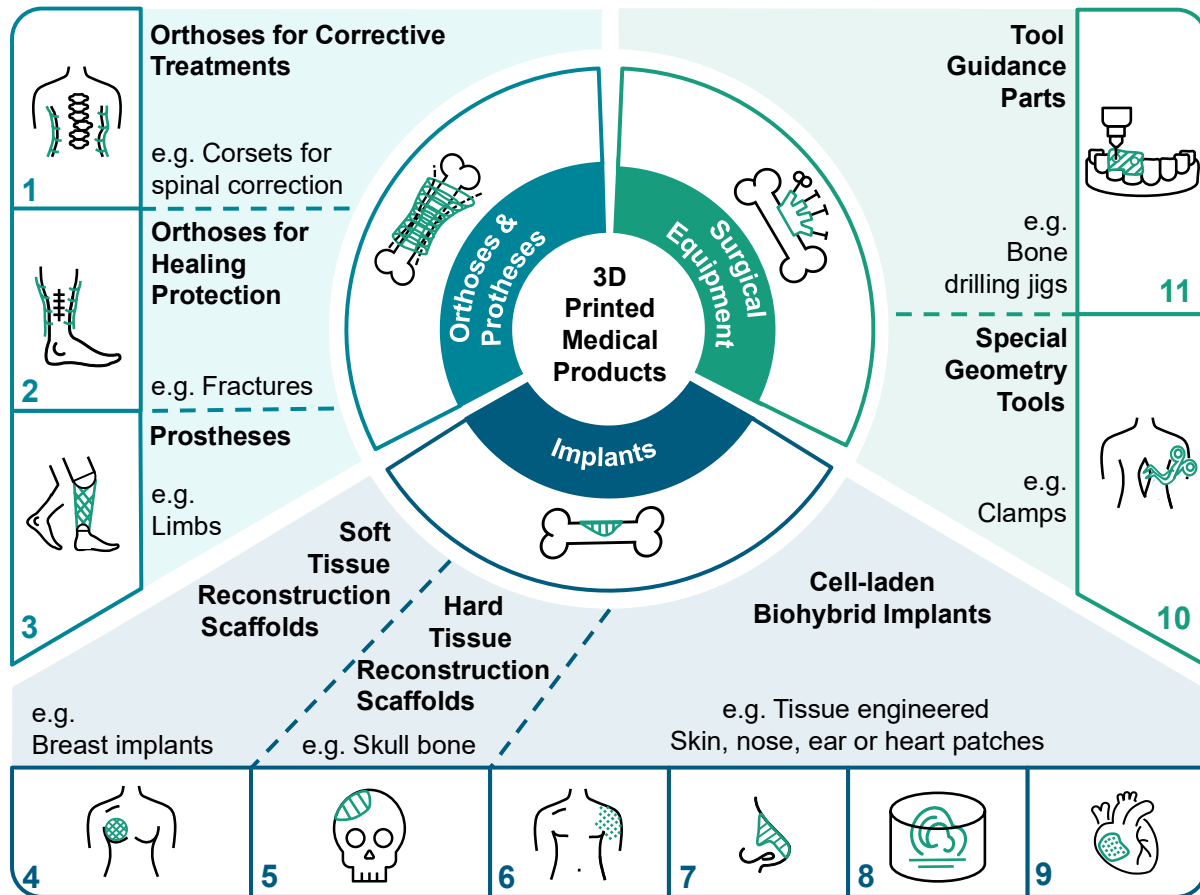


Figure 1: Sub-categorized applications for personalized 3D printed medical products

To gain insight into the current state of the art regarding the industrial production of personalized 3D printed medical devices, an anonymous survey was conducted with companies in this sector. Responding to the call for participation, four companies submitted answers to most of the questions. The content of the questionnaire and the complete answers are shown in Annex A.2. In the survey results, all companies confirm that their production is little or not automated and digitized. Three companies state that they plan to significantly increase their production throughput within the next five to ten years. Two companies consider it a current or future challenge to find technical solutions for fully automated production that meet their requirements for potentially growing product demands.

Despite the limited response rate of 18 % to the questionnaire, a practice-relevant problem can be identified. This problem is described as a lack of automated, scalable production infrastructure for EAM-based manufacturing of personalized medical devices. Publications in this area confirm that this is a topic of relevance (Conway et al., 2024; Parulski et al., 2021). In the following subchapter, this problem statement is further elaborated.

To narrow down the scope, this work focuses on the product category of scaffold implants, see Figure 1 (5) and (6). This category is selected because they represent a significant market share among personalized medical products with a market volume of 2,34 billion USD in 2024, expected to reach 8,58 billion USD in 2034 (Globe Newswire, 2024; Grand View Research, 2022). As a continuation of a previous publication (Janning et al., 2025), a production infrastructure for the scalable manufacturing of personalized medical scaffolds is conceptually developed and validated. The term production infrastructure encompasses not only the additive manufacturing process, but also intralogistics and structural requirements for the production environment. Central innovations of this development are investigated using a physical demonstration system. Also, this work is motivated to focus on the digital modeling of a personalized scaffold production to meet the state of the art in terms of digital production. This model is developed, validated and used to simulatively investigate approaches regarding production scaling and optimization. Ultimately, this work demonstrates new approaches for the production of EAM-based scaffolds and provides methodological and conceptual guidance for companies to improve their production.

1.2 Problem Statement and Objectives

Based on the initial situation described in Chapter 1.1, the problem is further elaborated in the following to derive specific objectives and to determine a suitable research approach. In a generalized form, the root problem can be described by the statement that the current production of medical scaffolds using EAM is affected by multiple inefficiency factors (Johansson, 2016; Liaw et al., 2021; Ramian et al., 2021; Sani et al., 2024). To identify the causes of these inefficiencies, an Ishikawa analysis is carried out (Ishikawa, 1996). Therefore, using the classic 6-M Ishikawa diagram structure, an explorative literature review is conducted to qualitatively identify causes connected to the problem statement. Figure 2 shows this diagram with the causes of the first order (blue) and correspondingly the causes of the second order (green).

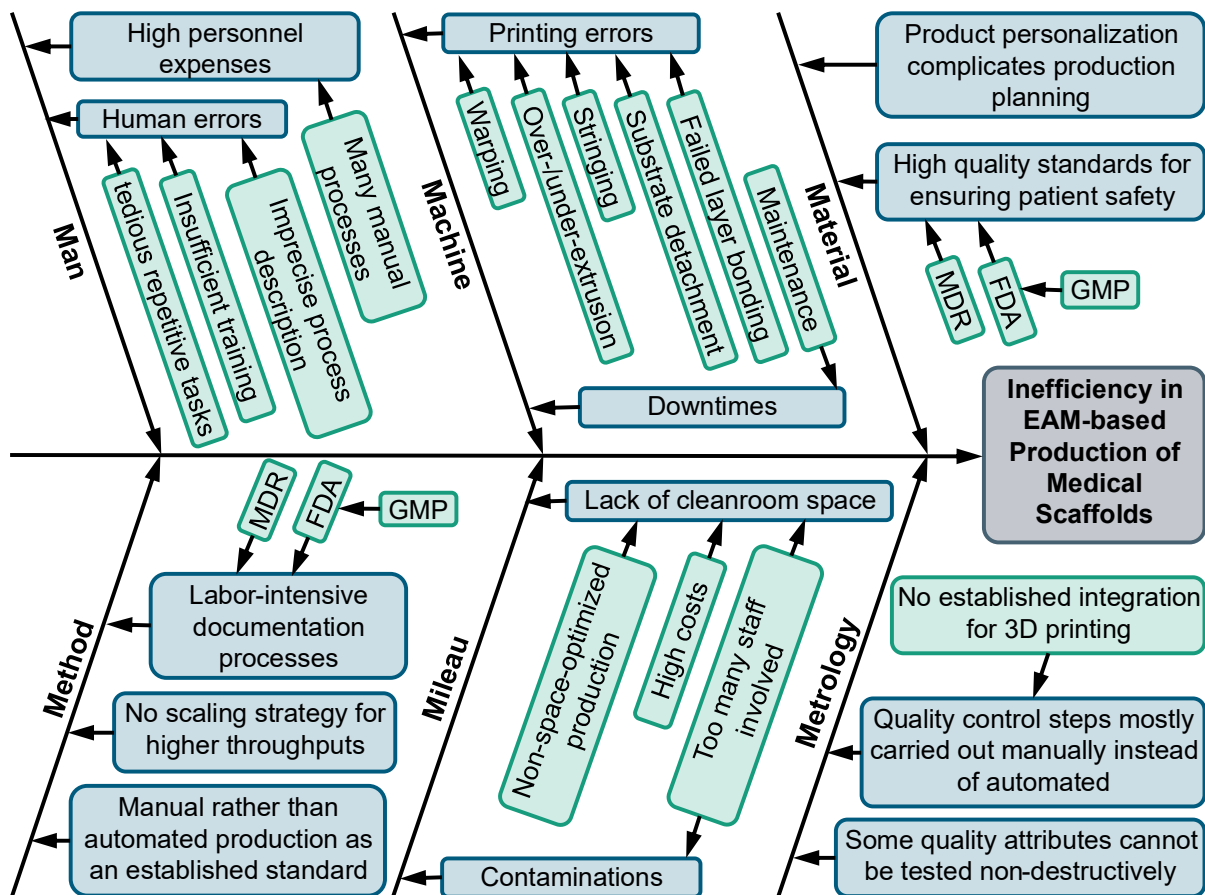


Figure 2: Ishikawa diagram for the collection of possible influencing factors for inefficiency in the EAM-based production of personalized medical scaffolds

Summarizing the results of the Ishikawa analysis, it can be stated that a significant proportion of the causes can be traced back to a lack of automation or could be avoided by automating. High personnel expenses and the occurrence probability of human error and contamination can be avoided by involving fewer personnel in the direct manufacturing process through automation. This could also increase the reproducibility of quality. Labor-intensive documentation in compliance with regulations can also be improved through digitization approaches. Ultimately, the footprint of production can also be minimized through space-optimized automated systems, saving expensive cleanroom area. Even if the probability of occurrence of printing

errors cannot be significantly reduced by automation alone, digitization and corresponding production models can help to enable a predictive quality management, which can ultimately reduce the impact of errors on production efficiency. Even if not all reasons can be ascribed to a lack of automation, the assumption can be supported that improved automation solutions for EAM would improve the production conditions of personalized medical scaffolds.

The **problem statement** is thus defined as **the lack of automated, scalable production infrastructure for EAM-based manufacturing of personalized medical scaffolds**.

On this basis, a target state can be defined. Figure 3 exemplary illustrates both the initial state and the target state. The initial situation with regard to scaffold production, which could be outlined using the insights gained from industry, can be described as follows:

In the initial state, the production is manual and of low technical complexity. The EAM devices are located in a cleanroom and are operated in parallel according to production demand. Based on an average scaffold size with a mass of 50 g, it is estimated that up to 50 products per week can be produced with one printer in a 12 m² clean room. This assumption was made on the basis of experience values obtained by surveying relevant companies. For this, it is necessary that the individual prints are always started and monitored by appropriately trained and equipped personnel. A three-person shift operation would therefore be necessary. The handling of the printing materials, as well as the finished products, is done manually. Individual process parameters such as temperatures or cleanroom parameters can be monitored automatically, but the printed products quality is inspected manually. Documentation is done semi-automatically using a Laboratory Information Management System (LIMS).

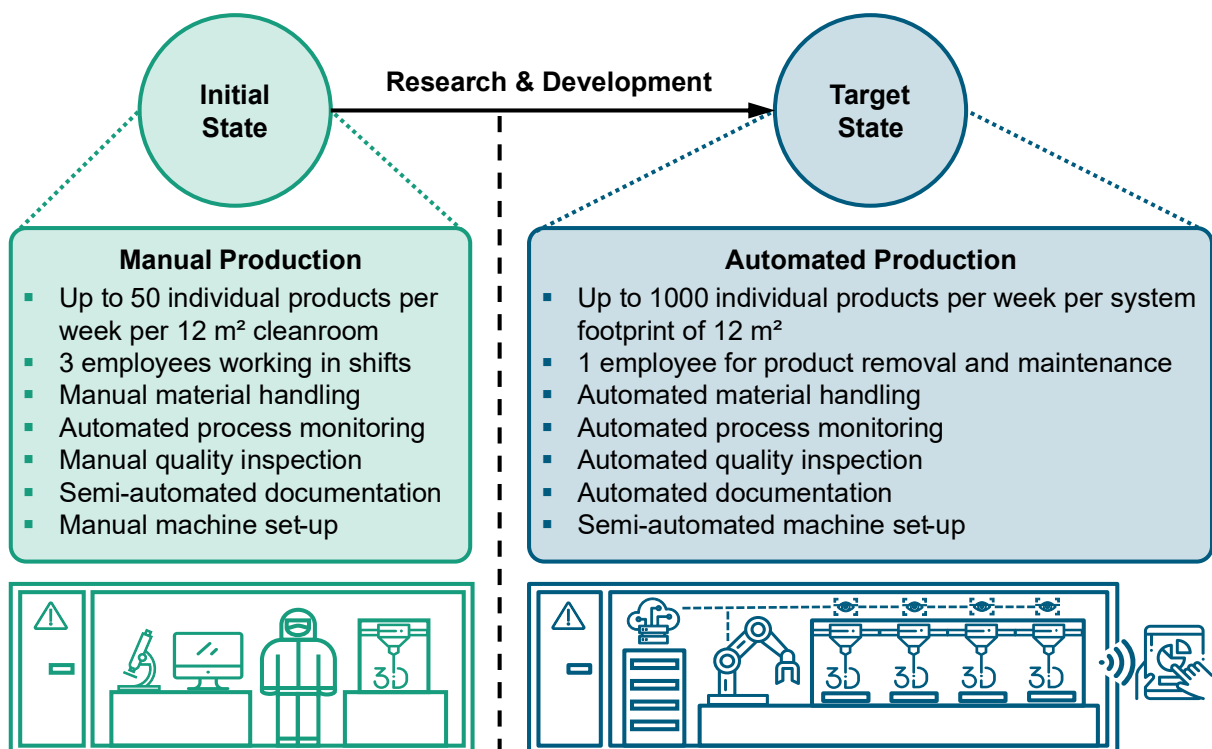


Figure 3: Exemplary illustration of the initial and target states in terms of individualized EAM-based scaffold production

The target state represents a fully automated production. Here, up to 1000 personalized products per week can be produced with a system with a 12 m² footprint. This value is based on the desired capacities that emerged from the industry survey and also reflects market developments. One employee is required for the initial set-up of the system and ultimately the removal of the finished product batches, as well as for machine maintenance. All intralogistics steps in production, as well as process monitoring, product quality control with recording and documentation of the results, would be processed automatically. The figure indicates that the manual production approach would not achieve the same desired efficiency in terms of personnel requirements and cleanroom space with a scale-out approach by adding additional printers. Accordingly, the entire production approach must be rethought in order to realize the outlined target state.

In order to cross the barrier between the initial state and the target state and to enable fully automated scalable production of personalized scaffolds, extensive research and development measures are necessary. The utilized research approach, which determines the structure of this work, is derived in the following chapter.

1.3 Research Approach and Thesis Structure

The approach of this work is to proceed from a defined production problem to a solution for this problem by following a systematic research process. This solution, or target state, is characterized as described in the previous chapter and comprises the following three aspects for the aimed production infrastructure:

- Fully automated and scalable
- Regulatory compliant
- Individualized for personalized products

For the research required for this, four relevant research questions are derived in the following. Since this work is located in the field of applied research with a specific practical relevance, a development process proceeds in parallel to the research process, in which a correspondingly qualified production concept is developed. The research process is based on the recommendations of Ulrich (Ulrich and Hill, 1976) and this thesis is structured accordingly. The development work utilizes established industry standards such as those from the Association of German Engineers (VDI). Based on this, a physical demonstration system and a digital production model are developed, which in turn are then used to validate the concept. The individual development results then serve as a tool for answering the research questions. Figure 4 broadly visualizes the research and development approach.

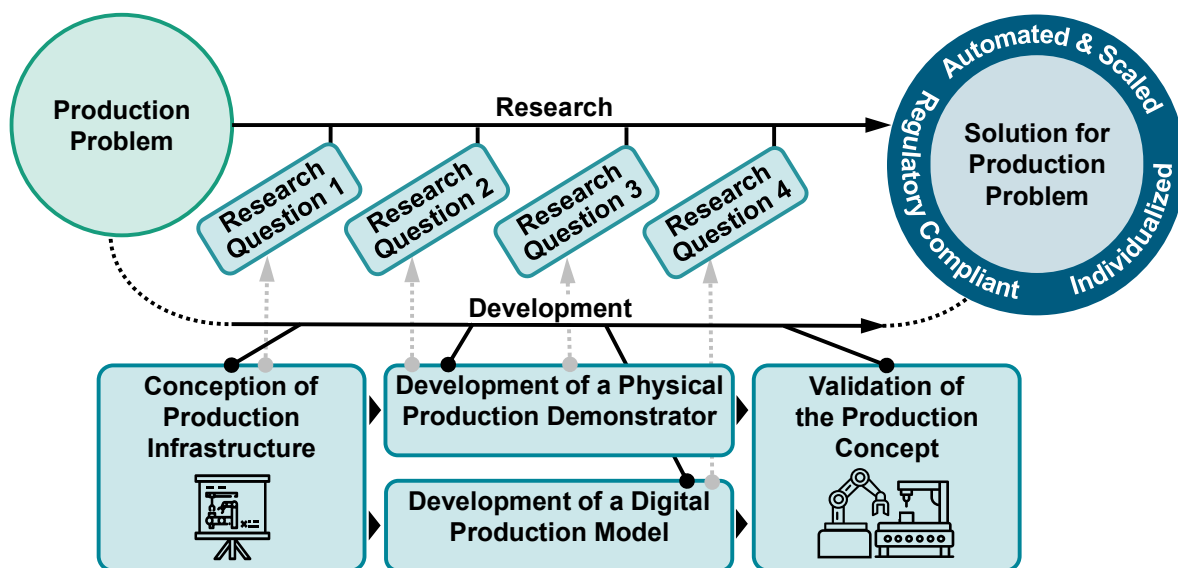


Figure 4: Simplified illustration of the research and development approach of this thesis

The research questions deal with the systematic identification of relevant requirements, the conceptual design of automation solutions, the digital modeling of a production infrastructure and its scalability and optimizability. In the following, the main research question and the associated sub research questions are specified.

Research Questions

The main research question (MRQ) that this work is committed to answer, is formulated as follows:

MRQ: Can extrusion-based additive manufacturing of personalized medical scaffolds be end-to-end automated for a scalable production?

The first sub research question (SRQ1) addresses the systematic identification of all relevant technical and regulatory requirements and is formulated as follows:

SRQ1: Which process parameters of EAM influence the quality attributes of medical scaffolds and what are the technical and regulatory requirements for production?

The second sub research question (SRQ2) addresses the development of the concept for an automated production infrastructure and is formulated as follows:

SRQ2: How can the process steps be automated for a scalable production of personalized scaffolds?

The third sub research question (SRQ3) addresses the development of a realistic digital representation of the production infrastructure and is formulated as follows:

SRQ3: How can an automated scaffold production infrastructure be digitally modeled?

The fourth sub research question (SRQ4) addresses the scalability and optimization of the production based on the digital model and is formulated as follows:

SRQ4: Can the digital production model be used for production planning regarding scalability and optimization?

Thesis Structure

Ulrich's research process is used to systematically and structurally address problems in applied sciences. The approach is most prevalent in engineering and in economics to analyze complex problems and develop problem-oriented solutions (Ulrich and Hill, 1976). A typical example is the systematic development of new technical systems, which applies to the introduced subject of this work.

Thus, the structure of this thesis is aligned with the seven steps of the research process according to Ulrich. Figure 5 shows these steps and illustrates the links to the individual chapters of this thesis (Ulrich and Hill, 1976). First, the problem relevant to practice is identified and typified (A). This is presented in Chapters 1.1 and 1.2.

Then the stated problem is investigated in more depth in the state of the art in Chapter 2, setting the topic in relation to current research (B). Problem-relevant theories and concepts are identified and interpreted, regarding problem relevant requirements. The next three steps, according to Ulrich, for identifying a suitable development methodology (C), comprehensively

investigating the application context (D), and deducing results in the form of technical concepts or models (E) are all addressed in the two main Chapters 3 and 4. Step (F) according to Ulrich on testing the rules and models in the application context is carried out within the testing and validation in Chapter 5. Both physical experiments and model simulations are conducted. The critical discussion of these validation results is presented in Chapter 6. The discussion also addresses the transferability to other applications, which, according to Ulrich, is assigned to the step of practice consultancy (G). In addition, the outlook in Chapter 7 highlights which research needs remain and which potentials the results have for practical implementation.

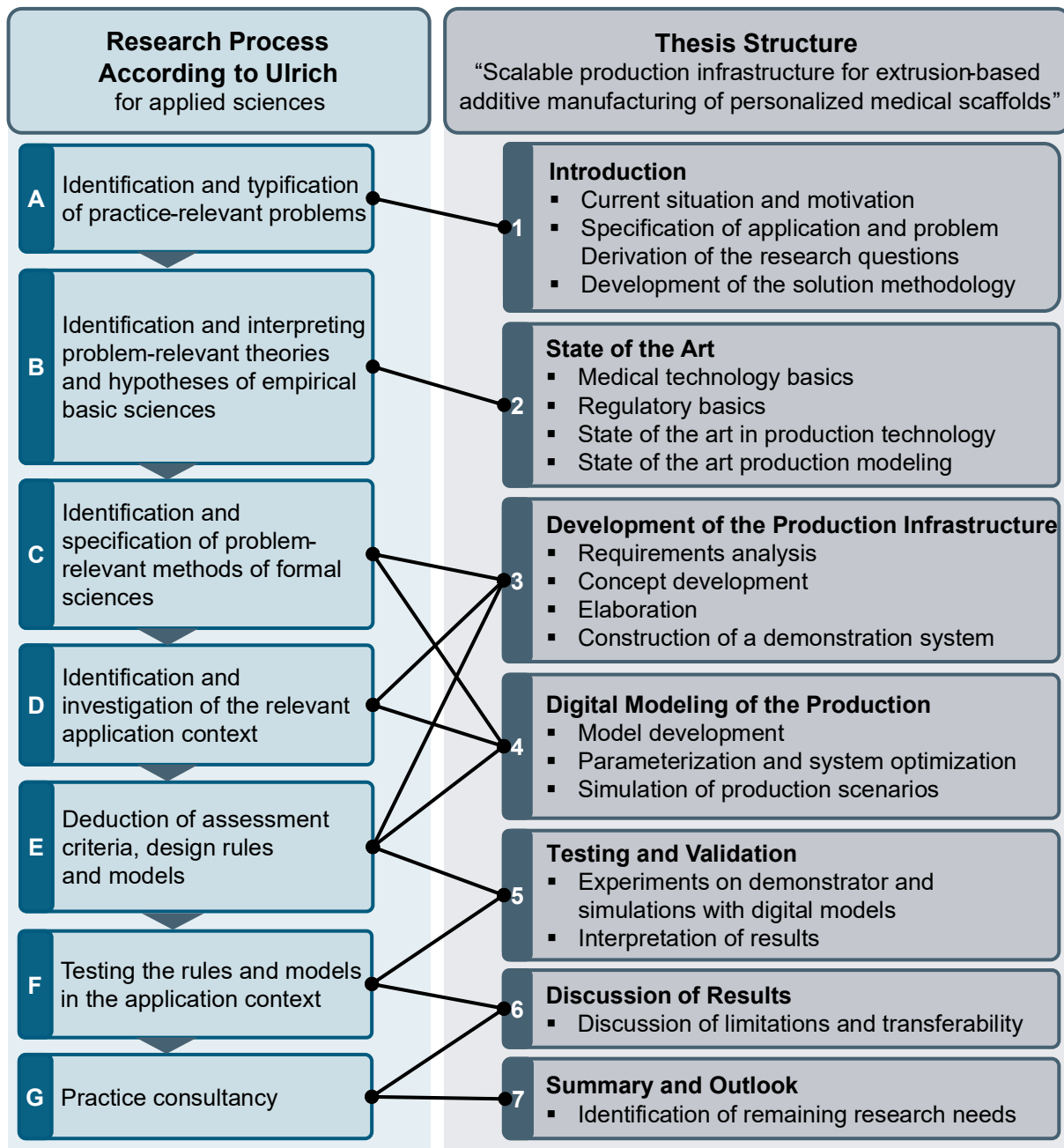


Figure 5: Thesis structure according to the research approach by Ulrich (Ulrich and Hill, 1976)

The following Chapter 2, which explores relevant topics on the state of the art, addresses phase B of Ulrich's research process.

2 State of the Art

The foundation for the conceptual design of a scalable production infrastructure for personalized medical scaffolds is created by first introducing the personalized medicine approach and the respective products in order to gain an understanding of their requirements. Second, the key technology of extrusion additive manufacturing is examined in detail. The technical functioning of three-dimensional printing is explained, with an additional focus on the magnetic planar drive technology, which is a central technology of the conceptualized system. Subsequently, a systematic literature review is used to determine which process parameters are relevant in extrusion additive manufacturing and which quality attributes are important for medical scaffolds. Thereafter, the different forms of scaffold defects that can occur during the manufacturing process are identified. Thirdly, the regulatory framework for the manufacture of medical devices is considered and all requirements for the production and quality management, derived from the legislations, are collected. Fourthly, the foundations in terms of production infrastructure for biomedical applications is considered, with a focus on the requirements and design of appropriate cleanrooms for medical device manufacturing. Fifth, the technical aspects of production are described in more detail. The focus is set on the decoupled production approach and in particular on multi-agent path finding for its realization. Finally, the current state of the art in modeling production environments is explained. In particular, the event-discrete simulation is presented and, lastly, established key performance indicators are outlined, which can be used to evaluate and optimize production scenarios using simulation.

2.1 Personalized Scaffolds for Regenerative Medicine

Regenerative medicine is an interdisciplinary field that aims to regenerate damaged cells, tissue or organs by using biotechnological approaches to activate the body's own repair mechanisms (Atala, 2009; Jungebluth et al., 2015). One approach in this area is the use of personalized medical scaffold implants, which serve as structural supports for cell growth and tissue formation. These scaffolds are made of bioresorbable materials and are individually customized to the anatomical and biological requirements of the patient (Kim et al., 2019; O'Brien, 2011; Xu and Ivanovski, 2025).

A typical treatment workflow for personalized implants begins with patient-specific imaging, for example using computed tomography (CT) or magnetic resonance imaging (MRI). The data obtained is used to create a digital 3D model that serves as the basis for the implant design. This model is then transformed into a porous scaffold geometry. Special software, known as slicers, then processes this design further into geometric code, which consists of stacked two-dimensional geometries, required to produce the scaffold layer by layer. The implant is then produced using 3D printing (Xu and Ivanovski, 2025). The production requires correct parametrization to achieve porosity, mechanical properties, as well as the biodegradability to be precisely adapted to the target tissue. In this context, legislations require that both the design of the production infrastructure and the quality management system meet specific requirements that apply to class III medical devices, compare Chapter 2.3 and 2.4 (Xu and Ivanovski, 2025). After scaffold production, the implant can either be finalized *ex vivo* by culturing it in bioreactors as a biohybrid implant by inducing hydrogels and seeding cells. Alternatively, the scaffolds can also be implanted directly and colonized *in vivo* by, for example, an autologous fat injection. After implantation, the scaffold serves as a temporary matrix for cell adhesion, proliferation and the formation of the body's own extracellular matrix (Chhaya et al., 2015). Over time, the scaffold is biodegraded and metabolized via the citrate balance until it is completely resorbed and replaced by the body's own tissue (Chhaya et al., 2015; Xu and Ivanovski, 2025). Figure 6 shows scaffold examples and illustrates a simplified workflow for the use of personalized medical scaffolds. This process is applied to various applications, such as the following:

- Breast reconstruction after mastectomy due to breast cancer (Chhaya et al., 2015; Visscher et al., 2017; Zhang et al., 2025)
- Aesthetic camouflage for severe pectus excavatum cases (Cheng et al., 2022)
- Bone regeneration for the treatment of bone fractures or defects (Chen et al., 2023; Khalaf et al., 2022; Mommsen et al., 2024; Zhang et al., 2023)
- Cartilage regeneration in knee joints for the treatment of osteoarthritis (Abdelhamid et al., 2023; Liu et al., 2021; Wu et al., 2022)

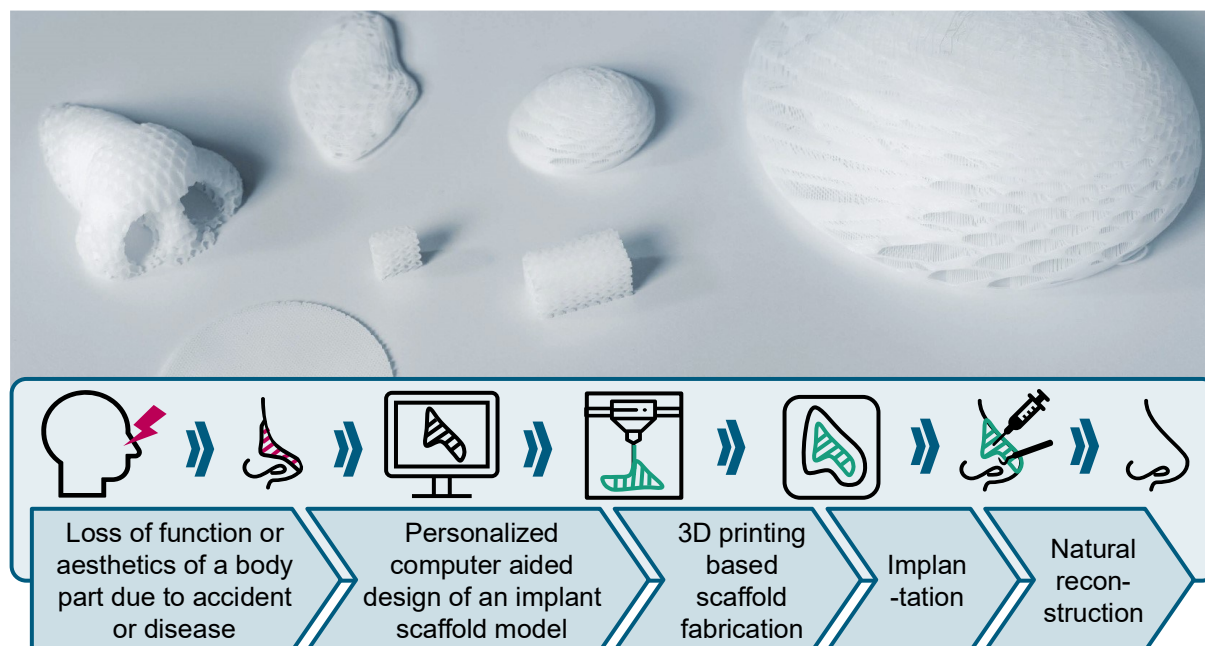


Figure 6: Simplified illustration of the workflow for the treatment of patients using personalized scaffold implants (Xu and Ivanovski, 2025), Image: (Bellaseno, 2024)

Personalized approaches can accelerate healing processes, minimize rejection reactions and improve the functional regeneration of tissues (O'Connor and Blau, 2019; Schroeder et al., 2022). These advantages are also reflected in the positive market development of regenerative medicine. More and more clinical data with successful therapeutic applications are being published and the number of approved products and therapies is increasing (Globe Newswire, 2024; Grand View Research, 2022).

2.2 Extrusion Additive Manufacturing

Extrusion-based three-dimensional (3D) printing is an Additive Manufacturing (AM) technique, which is also referred to as Extrusion Additive Manufacturing (EAM). The technique is also known as 3D Material Extrusion (MEX), Fused Deposition Modeling (FDM®), or Fused Layer Modeling (FLM). These terms, according to ISO/ASTM 52900:2021, describe the same technology and can be further categorized into Fused Filament Fabrication (FFF) and Fused Granulate Fabrication (FGF) depending on the raw material form ((Deutsches Institut für Normung e.V., 2021a)).

The principle of EAM is based on the creation of layers by extruding liquid or semi-liquid material through an orifice or nozzle. The material is dispensed directly onto a print bed or a substrate-carrying platform, which is optionally heated to achieve better adhesion. To enable vertical layering, the EAM machine used, must have three translational degrees of freedom. The basic design of an EAM system is shown in Figure 7 (Bergs, 2024; Gebhardt et al., 2016).

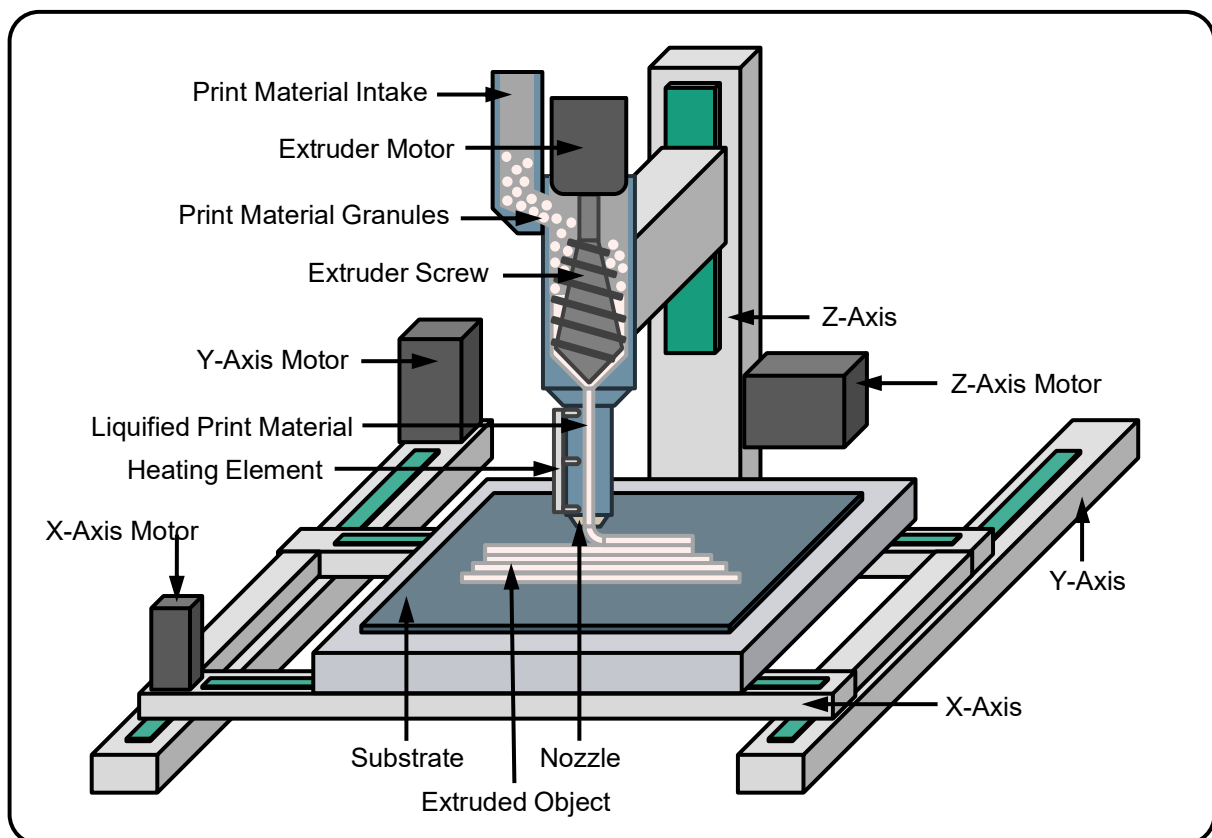


Figure 7: Basic structure of an FGF EAM system with gantry axis kinematics

The horizontal axes of the EAM system execute the positioning steps that are read from the Geometrical Code (G-Code). G-Code is a common programming language in Computer Numeric Control (CNC) and has become established in additive manufacturing (Satyanarayana and Prakash, 2015; Smid, 2008). For the vertical Z-axis, an initial leveling step is performed to define the zero height, after which the axis is moved by the corresponding layer height for each subsequent layer.

2.2.1 Kinematics of Three-dimensional Printing

Contrary to a gantry system, which operates three individual linear axes in parallel to achieve the three degrees of freedom, multiple other architectures exist and are presented hereafter.

Delta kinematics are a special type of parallel kinematics used in 3D printers for high velocities. Three symmetrically arranged arms control a movable platform with the print nozzle, resulting in a low movable mass and thus high dynamics. This enables faster print speeds and consistent print quality. Another advantage is the cylindrical build space, which allows for a compact design while maintaining a large print volume. However, the complex control system requires powerful algorithms to precisely coordinate the movements. In addition, accuracy can decrease in the peripheral areas of the print volume. The limited mechanical stability at high speeds can also lead to vibrations and thus to quality losses (Berge, 2024; Zakharov et al., 2022).

Robotic arms as the kinematic for 3D printers represent an alternative to conventional cartesian and delta systems. In this case, a multi-axis robotic arm positions the print nozzle, enabling a high degree of flexibility and an expanded manufacturing spectrum. This technology is particularly used in industrial applications where complex geometries and non-planar printing processes are required. Due to the large number of joints, printing processes can be carried out in several directions and on curved surfaces. In addition, the scalability of robotic arms makes them suitable for large-format prints that would be difficult to realize with conventional printing systems. Despite these advantages one of the biggest disadvantages of using a robotic arm for 3D printing is the complex control and calibration. Since the robot arm has non-linear kinematics, the precise coordination of the movements requires elaborate algorithms and powerful control hardware. This increases both development time and operating costs. Furthermore, robotic arms are generally more expensive than conventional cartesian or delta systems. Another problem is movement accuracy. While cartesian systems often offer high repeatability, robot arms can suffer from deviations due to mechanical tolerances and looseness in joints. This can negatively affect print quality, especially in high-precision applications (Anand et al., 2024; Jing et al., 2023).

Planar drive systems are not an established technology as kinematics for 3D printing. This concept is introduced in the context of this thesis, which is why the properties of magnetic planar drives are outlined at this point. Planar drive systems use magnetic fields to move objects in a planar plane. The movement is generated by the interaction of permanent magnets and electromagnetic fields. This can enable movement without mechanical contact, resulting in an elimination of friction and abrasion (Jansen et al., 2008). Magnetic planar drives are used in areas such as contactless positioning, precise motion control in manufacturing systems or automation technology, as they offer high accuracy and speed with low maintenance. The technology is relatively young and was first introduced in the form of a commercially available product by Beckhoff Automation in 2019 (Beckhoff Automation GmbH). Accordingly, the range of yet established applications is limited. The most common design of planar drives is based on a stator system consisting of an electromagnetic coil array that generates a magnetic field capable of levitating one or more permanent magnets. By shifting the magnetic field by

appropriately changing the current in the coils, the movers can then be moved while levitating. Levitation heights of up to 5 mm are possible. In addition to planar movement, movements in all six spatial degrees of freedom are possible. This includes rotation around the vertical axis and slight tilting by a upto ten degrees around the horizontal axes, as can be seen in Figure 8 (Janning et al., 2022; Wang et al., 2024).

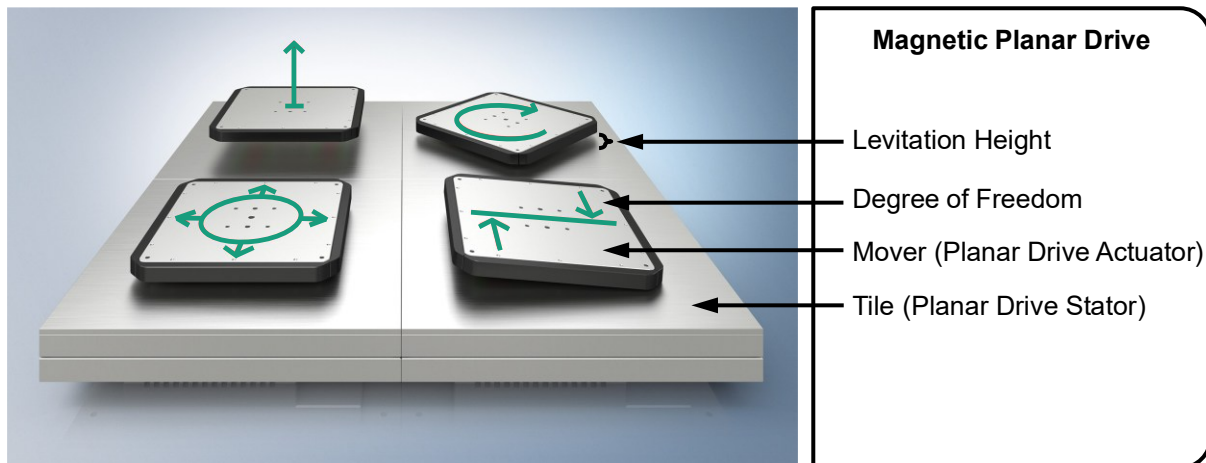


Figure 8: Visualization of a magnetic planar drive system with its components and the movement degrees of freedom; Image: (Beckhoff Automation GmbH)

The technology has become most established in the field of production intralogistics, where it is used to transport components between processing stations. A key feature of magnetic planar drive technology is the ability to move multiple transport units, known as movers, independently of each other within a single system. Instead of following fixed implemented paths, the target coordinates of each mover can be adjusted at any time, thus allowing free adaptability of the process chain (Janning et al., 2022). This is referred to as decoupled production. Chapter 2.5 provides a deeper insight into this topic and for the path planning of multiple agents.

In addition to the parameters that are given by the mechanical axes, which can influence the quality attributes of the desired 3D printed products, there are numerous other process parameters that have an influence. The following literature review identifies systematically which process parameters (PP) and quality attributes (QA) exist for EAM.

2.2.2 Systematic Literature Review on Extrusion Additive Manufacturing

The following literature research is based on the recommendations of Brocke (Brocke et al., 2009). In order to systematize this process, the scope of the literature review is divided into three phases and the search processes are explained in the following.

In **Phase I**, the scope and the desired results are defined. For this purpose, Cooper's taxonomy of literature research is used and shown in Table 1 (Cooper, 1988).

Table 1: Taxonomy of literature research according to Cooper (Cooper, 1988)

Characteristics	Category			
1 Focus	Research Outcomes	Research Methods	Theories	Applications
2 Goal	Integration	Criticism	Central Issues	
3 Perspective	Neutral Representation		Espousal of Position	
4 Coverage	Exhaustive	Exhaustive and Selective	Representative	Methodological
5 Organization	Historic	Conceptual	Methodological	
6 Audience	Specialized Scholars	General Scholars	Practitioners	General Public

In the context of this literature review, the research methods (1) by which process, and quality parameters were evaluated are of primary interest in order to be able to draw conclusions for subsequent conceptualization. Therefore, the literature research requires neutral representations (3) of previous research on central issues regarding process parameters and their influence on defined quality attributes (2). Since the aim is to cover as broad a spectrum as possible within the research topic with limited capacity, a representative literature search is aimed at, which makes a qualitative claim to the informative value (4). The results found are methodically summarized in categories (5) and are primarily aimed at scholars from the general field of additive manufacturing of medical scaffolds (6).

In **Phase II**, the inclusion criteria are established. This narrows down the considered scientific field and the literature to be selected. The selected criteria are listed in Table 2 and briefly explained below. The publication year is limited to focus on recent studies published after 2009, the year in which the patent for FDM 3D printing from the company Stratasys expired and the technology became open access. Accessibility is limited to open access publications but is extended by the access of the RWTH Aachen University and the Fraunhofer Gesellschaft to fee-based databases. Only publications in German or English will be considered to ensure a complete understanding of the literature. In addition, only original publications are used for the analysis to not further consolidate knowledge that has already been summarized.

Table 2: Inclusion criteria for literature selection

Criterion Type	Criteria
Year of Publication	Published from 2009 (15-year period)
Accessibility	Open access or access through resources of the RWTH Aachen University or the Fraunhofer Gesellschaft
Language	English or German
Publication Type	Original publications from scientific journals

In **Phase III**, suitable databases are selected and search terms defined. The following databases offer search options using operators and cover the subjects relevant to the research.

- Web of Science Core Collection: Interdisciplinary collection of publications
- Engineering Village: Engineering focused publications
- Embase: Medically focused publications

Semantic search engines (e.g. Google Scholar or Microsoft Academics) were not used to ensure the validity and reliability of the systematic literature search. When creating the search terms according to Brocke et al., thematically relevant subcategories are formed, which are then filled with search terms. These terms were iteratively adapted through trial searches in the databases in order to cover the subject area as precisely as possible (Brocke et al., 2009). Finally, the selection of search terms is defined in Table 3.

Table 3: Search terms to narrow down the content of the literature search

Reference to Content	Keywords
Medicine	biomedical OR medic* OR implant* OR tissue OR scaffold
Additive Manufacturing	FDM OR FFM OR FLM OR FFF OR FGF OR EAM OR MEX OR additive OR print* OR extru*
Process and Quality	process* parameter* OR process* optimi?ation OR PP OR CPP OR quality attribute* OR quality indicator* OR QA OR CQA
Material	biodegradable OR biocompatible OR biomaterial OR polymer*
Exclude	metal* OR titanium OR laser OR photopoly*

The publications are narrowed down by the defined framework conditions, but the search in the databases still yields 1844 hits. To ensure that the research is complete while remaining capable to screen efficiently, the selection of publications considered relevant must be systematized. To do this, the selection process is divided into four screening stages, which sequentially evaluate more of the publications' content and are used to check their suitability. Figure 9 visualizes the procedure for the literature research with the individual sighting stages.

1. Screening: Title and Formalities

The title and key terms must suggest that the article will make a meaningful contribution to the research question and the previously defined inclusion criteria must be met.

2. Screening: Abstract and Conclusion

The content is reviewed to determine whether the discussion of process parameters and their influence on the quality attributes can be expected. It must be clear that an EAM process was used to manufacture medical products.

3. Screening: Full-text Analysis

It is checked whether the information provided on process parameters and quality attributes is actually usable and of sufficient scientific quality.

4. Reverse Search

The bibliography of the papers considered relevant is searched for new, sources. In doing so, screenings 1 to 3 are repeated until no further literature is found.

Duplicates were recognized by the citation software Citavi and not considered further. A total of 30 publications were identified that met all content-related and formal criteria. Table 4 shows the number of publications considered in the selection process according to the procedure described. These publications are listed and briefly described in Annex A.3.

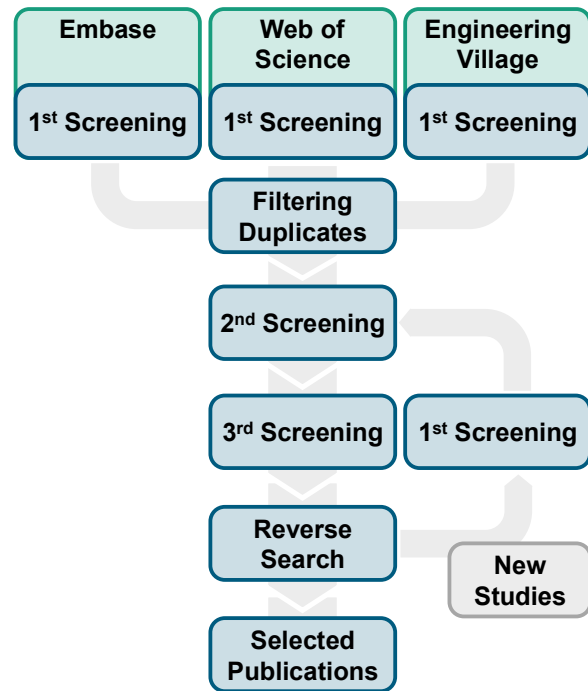


Figure 9: Screening structure of the systematic literature review

Table 4: Number of publications investigated in the course of the literature search

Database	Number of Publications		
	Embase	Web of Science	Eng. Village
Search results	77	747	1020
Results after first screening	23	101	97
Removed duplicates	0	11	36
Combined results after first screening		174	
Results after second screening		74	
Results after third screening		28	
Reverse search		2	
Selected publications		30	

2.2.3 Relevant Process Parameters and Quality Attributes

Process Parameters

Reviewing the 30 mentioned publications resulted in process parameters shown in Figure 10. These parameters are clustered to specific subcategories, such as temperature conditions, extrusion properties, geometry-related settings, or timing and environmental parameters.

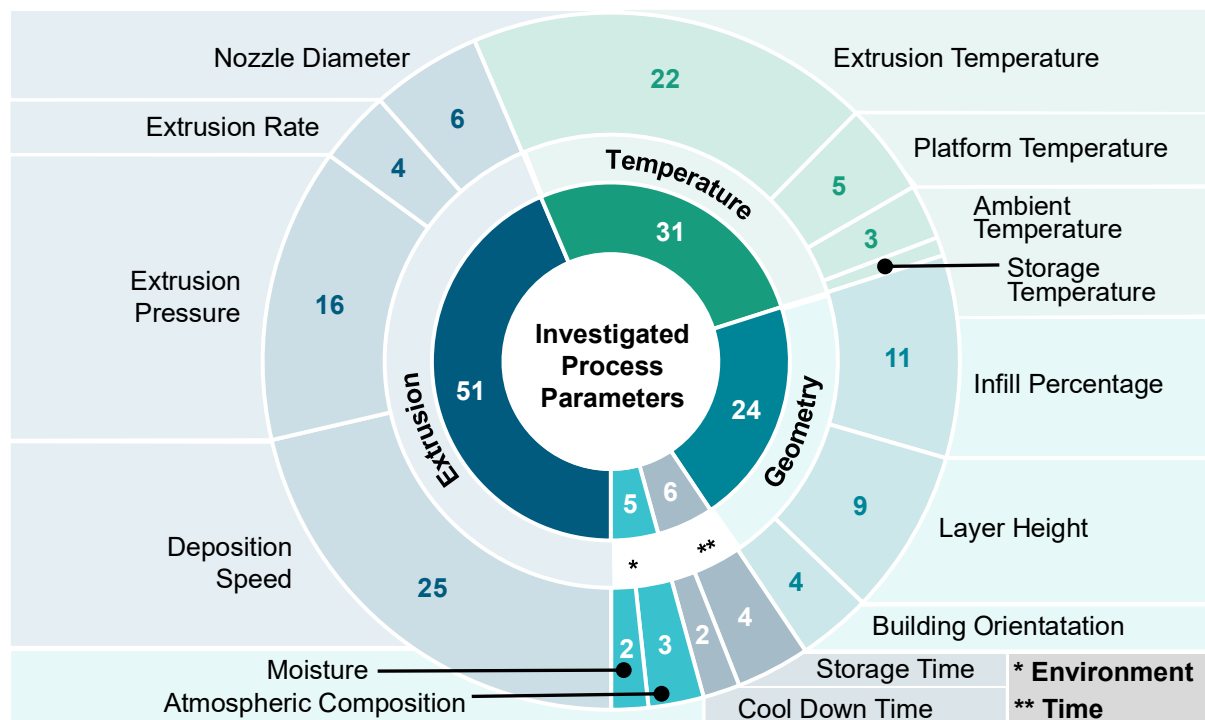


Figure 10: From literature identified process parameters of EAM. Parameters are listed and categorized with the number of times they are mentioned as relevant in the reviewed literature.

Extrusion

The extrusion category includes process parameters that describe the speed and quantity of the applied material. They are most frequently studied in the context of scientific research. The coordination of the individual process parameters of the material application is crucial for the accuracy of the printed structures and thus has a major influence on various quality attributes, such as dimensional accuracy (Myers et al., 2022). The extrusion results from the interaction of the following individual parameters:

The **deposition speed** describes the displacement per unit of time between the location of the extrusion start and the location of the extrusion stop (Bouzaglou et al., 2023; Rendas et al., 2023). The **extrusion rate** describes the volume extruded per unit of time. In research, **extrusion pressure** is often regarded as an indirect parameter for the extrusion rate, since it strongly influences the extrusion rate and is easy to measure and adjust in practice (Popescu et al., 2018; Winarso et al., 2022). The extrusion rate can be controlled by different mechanisms. In pressure-based extrusion, this is done either by mechanical or pneumatic pressure. In motor-based extrusion, the material feed is generated by the rotation of gears or extrusion screws (Bouzaglou et al., 2023; Rendas et al., 2023).

The **nozzle diameter** describes the size of the opening through which the material is dispensed and can be perceived as a geometric parameter, but it also has a significant influence on the extrusion. However, a smaller nozzle diameter does not necessarily lead to a smaller width of the printed material line. Rather, by exploiting the elastic behavior of the material, a finer structure can be achieved without changing the nozzle diameter (Brandley et al., 2018). Depending on the print material, the layer thickness usually takes on a value between 40 - 70 % of the nozzle diameter (Popescu et al., 2018; Winarso et al., 2022).

Temperature

The temperature category includes all process parameters that exert a thermal influence on the material. They have a significant influence on the viscosity and crystallinity of the material (Bouzaglou et al., 2023; Popescu et al., 2018; Rendas et al., 2023). The optimum temperature settings depend largely on the materials used and are composed of the individual process temperatures, explained in the following.

The **nozzle temperature** is the temperature to which the material is heated before it is extruded through the nozzle. Due to the volume expansion at high temperatures, the nozzle temperature also has an influence on the extrusion rate (Yang et al., 2016).

The **platform temperature** describes the temperature of the build platform. By heating and cooling, it contributes to the manufacturing quality and prevents manufacturing defects such as warping. This describes the detachment of the component from the build platform due to residual stress caused by cooling too quickly on the underside of the component (Bouzaglou et al., 2023; Rendas et al., 2023); compare Chapter 2.2.4.

The **ambient temperature** determines the cooling process of the entire component. The cooling process, in turn, determines the crystallinity of the material, which in turn influences the mechanical strength (Popescu et al., 2018; Rendas et al., 2023; Saini et al., 2022).

The **storage temperature** indicates the conditions under which the material is stored and then prepared for the printing process. Optimal storage conditions are usually specified by the material manufacturers and are crucial for the quality of the end product. Maintaining these conditions is essential to avoid material degradation prior to the printing process (Giorleo et al., 2021).

Geometry

This category includes process parameters that relate to geometric variables within the process. However, these are in most cases strictly predetermined by the product design, such as the **infill parameters** that define the density and internal structure of a component (Bouzaglou et al., 2023; Popescu et al., 2018; Rendas et al., 2023; Winarso et al., 2022).

The **layer height** indicates the displacement per layer in the Z-direction and is limited by the nozzle used. The layer height determines the surface quality and dimensional accuracy along the Z-direction. In addition, a low layer height is associated with a higher mechanical strength (Vijayasankar and Pati, 2023).

Building orientation is defined by how the component is oriented on the build platform relative to the X, Y, and Z axes of the machine. The way in which the quality attributes are influenced depends to a large extent on the printer used and the product design itself. (Bouzaglou et al., 2023; Winarso et al., 2022). The distance between the nozzle and the surface (of the build platform or part) can also be counted as a building orientation parameter and describes the distance traveled by the material after leaving the nozzle before it hits the platform, or the material already deposited. This is relevant for the cooling process of the material (Xie et al., 2023; Yang et al., 2016) but also for the accuracy of the filaments being placed (Yang et al., 2016).

Environment

The category of environment is rarely considered in science at present but can be important for future automated production systems. Process parameters that are considered in the context are the **ambient humidity** and composition. Also, the ambient temperature, which is already mentioned in the temperature category. The ambient humidity can influence the material properties of the printed structure. Excessive humidity can cause inaccurate and deliquescent structures (Alexander et al., 2019). If it is too low, there is a risk that components will dehydrate and become brittle during longer printing times (Kharel et al., 2019). The **composition** of the environment is considered in individual cases, for example, when the printing process is submerged in a supporting liquid (Ding and Chang, 2018). It would also be conceivable to conduct printing processes in a protective gas or vacuum environment for special applications.

Time

Process parameters with a time component are the storage time, the retraction delay time and the cool-down time of the material in the extruder.

The **storage time** describes the duration during which the materials are exposed to external influences that can lead to premature material degradation. These are often thermal influences that are generated by premature heating during pressure- and stress-based processes (Giorleo et al., 2021; Meng et al., 2021). The extruder **retraction delay** is the time the print head waits before moving to another position on the build platform. A longer delay time reduces stringing (Al Hashimi et al., 2022). Stringing is the formation of thin strings of molten material when the print head is repositioned; compare Chapter 2.2.4. This is accompanied by the extruder's **cool down time**, which describes the time that passes after the completion of a layer before the next layer is printed. During this time, the material can cool and solidify. Slower cooling rates produce higher crystallinity, to obtain a stronger polymer (Bouzaglou et al., 2023; Winarso et al., 2022).

Differentiation from material and design parameters

It should be noted that, in addition to the process-related parameters, there are further factors that influence the properties of the printed scaffolds. These originate in two further areas in particular: The design of the product and the choice of materials. Design measures, such as the determination of the infill density (Law et al., 2023) or the comb structure used (Myers et al., 2022) can influence the mechanical and biomedical properties of the medical product. The

choice of the optimal process parameters, in turn, depends on the material used. The material-related parameters include, the material supplements concentrations (Guo et al., 2017), the cross-linking strategy (Ning et al., 2018) and rheological properties of the material (Luis et al., 2020). All properties that are introduced into the process by the CAD model or the material are not taken into account to focus on manufacturing parameters instead of design parameters.

Quality Attributes

The precision and performance of 3D-printed medical products are contingent on the process parameters employed during their fabrication. The judicious control and optimization of these parameters is instrumental in ensuring the requisite mechanical properties, dimensional accuracy, and overall quality of the final product. The attributes by which the quality of EAM medical scaffolds can be evaluated are shown in Figure 11. The categories to which these attributes can be assigned include the geometric and mechanical properties of the printed product, as well as biomedical properties, which primarily relate to tissue engineering applications.

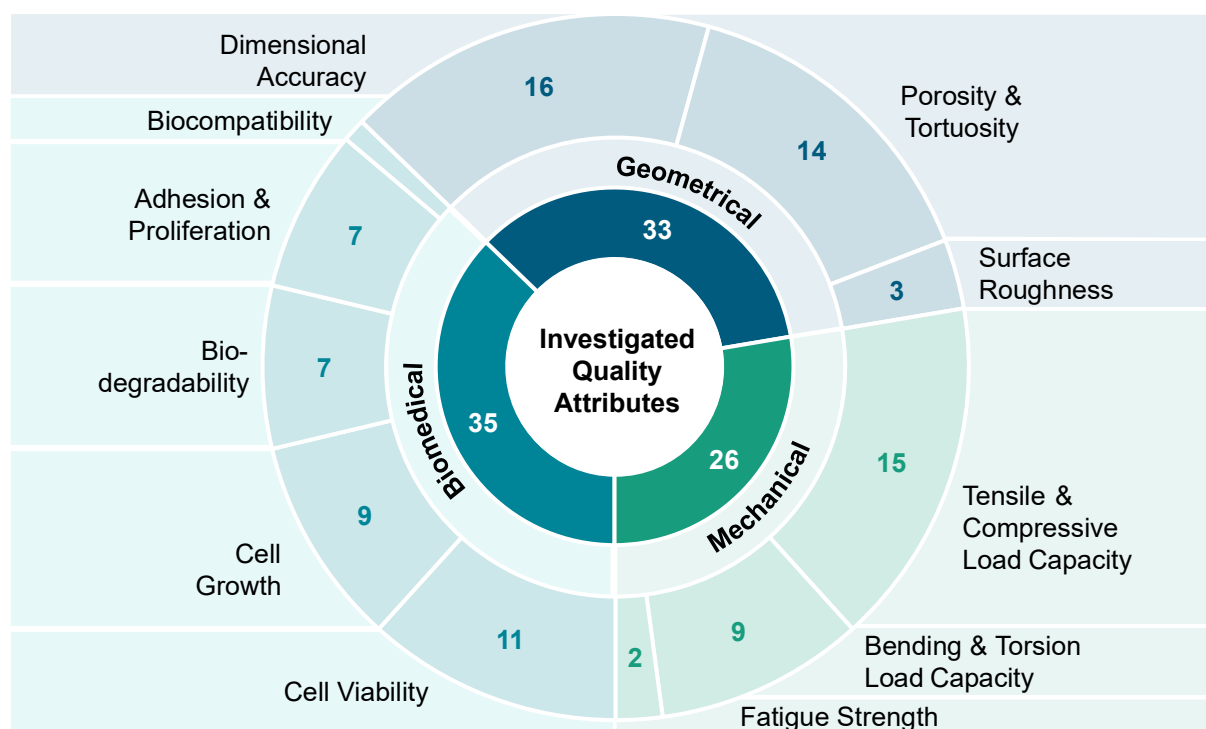


Figure 11: From literature identified quality attributes of EAM manufactured personalized medical scaffolds. Attributes are listed and categorized with the number of times they are mentioned as relevant in the reviewed literature.

All process parameters and quality attributes shown in Figure 10 and Figure 11 are derived from the reviewed literature, listed in A.3. Supplementary information regarding the respectively used methods and materials are listed in Annex A.4. These explanations are based on the full-text analysis from which nine key publications were identified, which provide detailed data-based descriptions of the individual parameters (Bahraminasab, 2020; Baier et al., 2022; Bouzaglou et al., 2023; Kovylin et al., 2021; Popescu et al., 2018; Rendas et al., 2023; Shick et al., 2019; Winarso et al., 2022; Zhang et al., 2019).

Biomedical

The biomedical attributes describe properties that can influence the behavior of medical devices in the human body. In research, they are often examined in the context of bioprinting or when scaffold structures are subsequently implanted or ex-vivo seeded with living cells. The attributes are used to evaluate the properties of these cells, to classify the influence of extrusion on cell behavior and to predict behavior in the human body.

The **cell viability** attribute indicates the proportion of living cells after extrusion. High cell viability indicates gentle processing and is the basis for the functionality and further proliferation of the cells (Rendas et al., 2023; Zhang et al., 2019). To maximize cell viability, external stresses must be reduced, for example by lowering the process temperature (Koch et al., 2022) or the tensile, compressive and shear stresses in the nozzle (Venkata Krishna and Ravi Sankar, 2023). On this basis, the **cell growth** attribute describes the behavior of the cells after extrusion. In research, various characteristics are considered, including cell adhesion, cell proliferation and cell differentiation (Baier et al., 2022; Shick et al., 2019; Zhang et al., 2019). Cell growth is positively influenced by two mechanisms. On the one hand, specific cells grow particularly well on rough surfaces, which is due to the high crystallinity of the material (Luzanin et al., 2023). On the other hand, specific pore properties promote the mineral supply and thus cell growth, for example, through better transport of nutrients and metabolic activities (Kim et al., 2017). The **degradation behavior** examines whether and at what rate the products age and to what extent their quality attributes change as a result (Baier et al., 2022; Shick et al., 2019; Zhang et al., 2019). The most common tests for this are based on the loss of mass and reduction in mechanical strength. Different material compositions are often the reason for different degradation behavior (Kharel et al., 2019). In contrast to this is the absorption behavior, which examines the absorption of substances and their influence on weight and geometry. In this context, water absorption is particularly examined, but also the ability to integrate minerals or proteins into the scaffold. Here too, the material composition is a decisive factor (James and Mulgaonkar, 2022). The attribute **biocompatibility** considers the compatibility of materials with an organism. (Kovylin et al., 2021; Zhang et al., 2019). To this end, the release of toxic substances is investigated, for example the release of nitrogen monoxide into the cell environment (Bachtar et al., 2020). Generally, the manufacturers of materials provide the qualification of materials for medical use, which is why this quality attribute is rarely examined separately in scientific research.

Mechanical

The category of mechanics encompasses quality attributes that examine the mechanical strength and stability of the printed constructs. These attributes are of central importance, as they provide the necessary structure and rigidity. In addition, the mechanical properties of implants should be adapted to the surrounding tissue so that cells differentiate accordingly (Baier et al., 2022). Mechanisms that have a positive effect on the mechanical properties include crystallinity (Saini et al., 2022) and the layer bonding (Koch et al., 2022), which can be significantly influenced by the temperature settings during the printing process.

The behavior under **compressive load** includes a range of different properties that characterize the product under the influence of compressive forces (Popescu et al., 2018). These include the compression modulus, the compressive strength and the compressive stress at break. On the other hand, there is the behavior under **tensile load**. Here, too, various properties are summarized, including the modulus of elasticity, the yield strength and the tensile strength. The **bending** and **torsion load** capacities are dependent variables that are also influenced by these properties but are also largely determined by geometric design factors. **Fatigue strength** describes the behavior under cyclic loading over a longer period of time and usually at stresses well below the yield strength. Nevertheless, an understanding of fatigue strength is important in medical applications, since some implants are exposed to high stresses in the body over many years (Rendas et al., 2023; Zhang et al., 2019).

Geometrical

The geometry category includes all quality attributes related to the geometric properties of the products. **Dimensional accuracy** describes all measurements during and after extrusion that consider deviations from a target value. The focus of the research is on the ability to produce a precise and consistent material string that can be used to reliably reproduce exact structures. Dimensional accuracy is influenced by several process parameters and mechanisms. To avoid over- or under-extrusion, the process parameters of the material extrusion must be aligned with each other (Myers et al., 2022). To minimize the material from deliquescing after extrusion, the process temperature must be adjusted to the material properties (Al Hashimi et al., 2022). If there are certain requirements for the product, for example small radii or particularly narrow line widths, the compatibility with geometric process parameters (e.g. the nozzle diameter or the nozzle distance to the surface) must also be checked (Fu et al., 2021b, pp. 185–186).

The quality attribute of **pore properties** combines a variety of parameters, including pore size, porosity of the component and the lattice angle between the layers. Overall, pore properties are frequently considered in the studies because they are also relevant for other quality attributes. Pore geometry, for example, has a direct influence on nutrient flow and metabolic activities in the process of cell mineralization and thus contributes significantly to cell growth. (Kim et al., 2017). When used as a bone substitute, the pore properties are crucial for the acceptance of the implant in the body and thus central to the long-term success of an implantation (Myers et al., 2022). The **surface quality** is determined by the nature of the product surface at the microscopic level. Surfaces that are characterized by high crystallinity are particularly suitable because they provide coarser structures for the cells to adhere to (Luzanin et al., 2023).

Further Findings of the Literature Research

Noticeably, the relevant process parameters and quality attributes differ depending on the product category. Two main categories can be distinguished. The first category includes cell-seeded products, or biohybrid implants, which consist of a biocompatible carrier material with living cells embedded in it. These are so-called bioinks and, depending on the application, may be accompanied by a polymer scaffold. The second category is cell-free applications. The products in this category are either scaffold implants, prostheses, orthoses or personalized

medical equipment, as shown in Figure 1. Figure 12 compares these two categories and shows how often each extrusion principle was used within the investigated literature, which materials were printed, and the most relevant process parameters and quality attributes. In both categories, it is apparent that the extrusion principle is the most often investigated and published 3D printing technique.

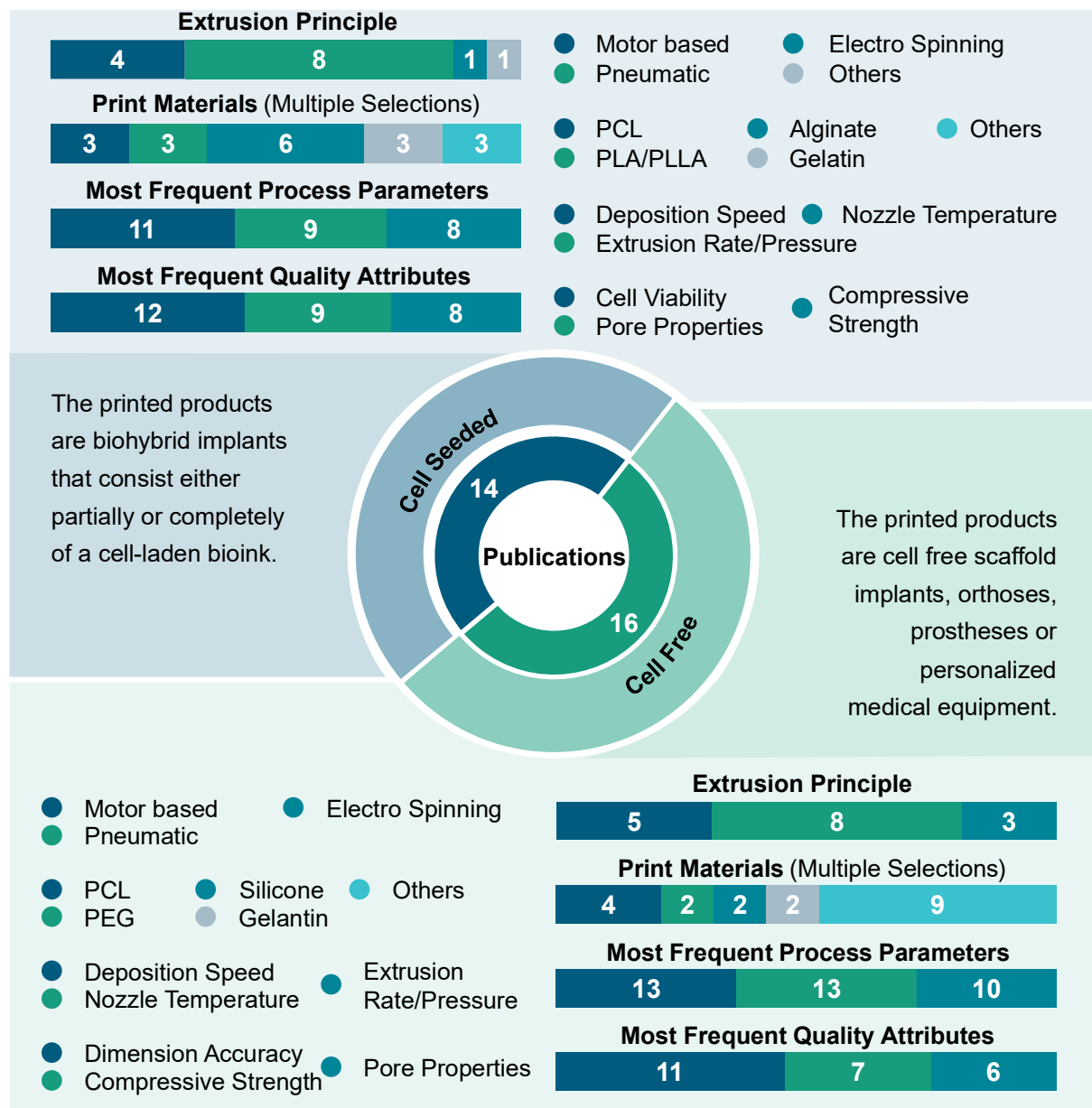


Figure 12: Comparison of literature review results for cell-seeded and cell-free medical scaffolds

The present study focuses on cell-free medical scaffolds. These scaffolds, when utilized as implants, can come into direct contact with cells; however, the cells do not impede the manufacturing process itself. Consequently, the conceptual design of the production infrastructure for cell-free medical scaffolds is carried out in Chapter 3.

2.2.4 Defect Causes in Extrusion Additive Manufacturing

As described in detail in the previous chapter, the quality of 3D-printed polymer scaffolds is determined by numerous process parameters. Incorrect parameterization of these can therefore lead to various defects. These defects can be caused either by individual process maladjustments or by complex interactions of multiple parameter fluctuations. Figure 13 schematically shows the most frequently occurring scaffold defect forms. In the following, their formation and influencing factors are explained based on the current state of the art.

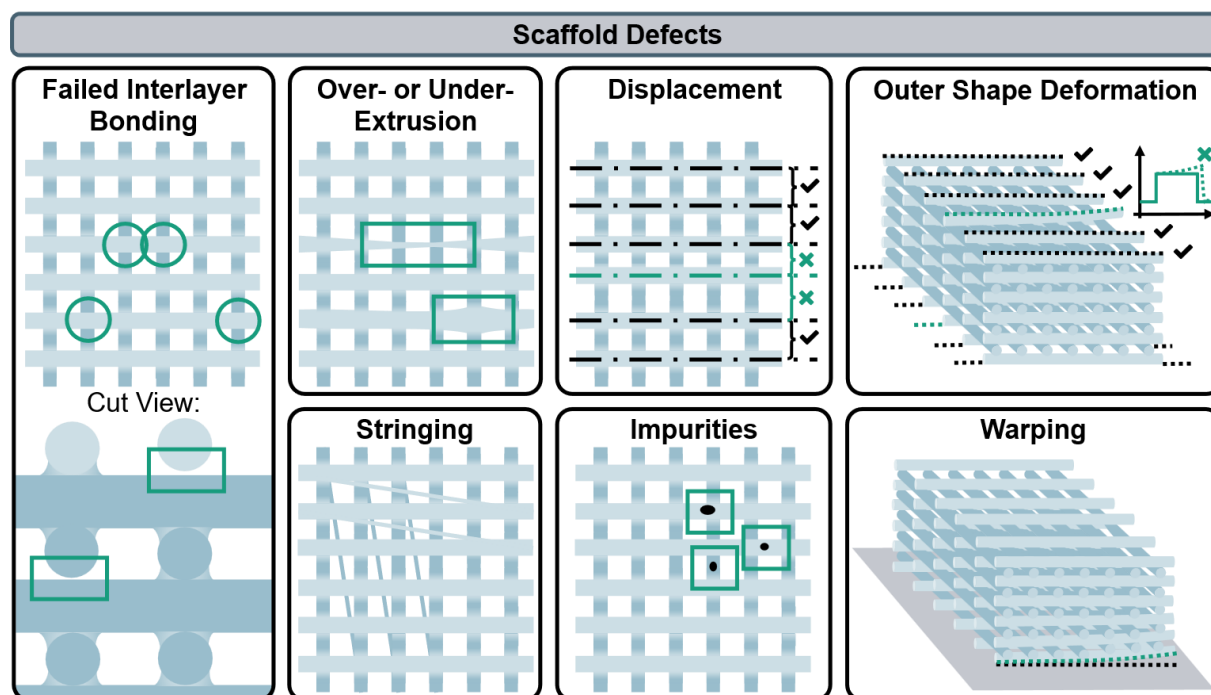


Figure 13: Schematic visualization of common defect forms in EAM

Failed Interlayer bonding

Defective interlayer bonding in EAM results from insufficient fusion of successive layers, which impairs the mechanical integrity of the component. Key influencing factors are the extrusion temperature, ambient conditions, printing speed and material flow rate. If the extrusion temperature is too low, the diffusion of the polymer chains between the layers is reduced, while an insufficiently heated build chamber can lead to delamination due to too fast cooling. If the printing speed is too low or the waiting time between layers is too long, the connection can also be weakened because the previous layer cools too much before new material layers are deposited. In addition, if the layer height is too high in relation to the nozzle width, insufficient adhesion can occur (Johansson, 2016; Liaw et al., 2021).

Over- or Under-extrusion

Over- and under-extrusion in EAM result from inadequate material feeding, which affects the dimensional accuracy and mechanical properties of the component. While over-extrusion leads to material excess, unclear surfaces and loss of detail, under-extrusion causes gaps, layer delamination and mechanical weakness. The main causes of over-extrusion are an excessive material flow rate, incorrect calibration of the extrusion multiplier or an incorrectly set

nozzle diameter. Also, too high extrusion temperature can reduce the viscosity of the filament, causing too much material to be extruded. Under-extrusion, on the other hand, occurs when the actual material feed is less than the amount demanded. This can be caused by an extrusion temperature that is too low, a blocked or worn nozzle, a faulty or inconsistent material feed, or excessive print speed (Sani et al., 2024).

Displacement

Displacement or dimensional inaccuracies in EAM describe deviations of the printed geometry from the design dimensions, which can affect the functionality of the component. These inaccuracies arise from mechanical, thermal and software-related factors. Mechanical causes include errors related to the axes and motors, such as insufficient rigidity of the printer structure or slop in the axis guides. Thermal influences such as uneven cooling and material shrinkage affect dimensional accuracy, especially with large or highly shrinking affected materials. Excessive printing temperatures or an insufficiently heated printing environment can also cause dimensional deviations due to uncontrolled material contraction. On the software side, incorrect step settings, wrong scaling factors or incorrect compensation parameters in the slicer software can negatively affect the precision of the printed geometry (Johansson, 2016; Sani et al., 2024).

Warping

Warping in EAM describes the uncontrolled distortion of a component during the printing process, which can lead to it detaching from the printing plate or causing severe dimensional deviations. This effect is primarily caused by thermal stresses resulting from uneven cooling and material contraction. Warping is particularly pronounced in materials with high shrinkage, because these materials contract when cooling. An insufficiently heated or unevenly tempered printing plate can impair the adhesion of the first layers, causing the edges of the component to bulge upwards. In addition, external factors such as airflow can increase the cooling rate locally and distribute stresses in the material unevenly. Influences, such as insufficient adhesion to the printing surface or excessive printing speeds or too short cooling times in the first layers, increase the risk of warping (Ramian et al., 2021; Shen et al., 2024; Singh, 2018).

Stringing

Stringing refers to the formation of fine threads between separate print areas caused by uncontrolled flow of molten filament during empty runs. The main causes are an inadequate retraction setting, an excessively high extrusion temperature or a travel speed that is too fast, causing the filament to stop too late or be pulled out of the nozzle unintentionally. Low-viscosity materials are particularly susceptible because they tend to flow just by gravitational pull. A contaminated or worn nozzle can also impair material control and promote stringing (Charia et al., 2025; Haque, 2020; Yean and Chew, 2024).

Impurities

Impurities are defined as inclusions of foreign particles in the extruded material. These are caused by contaminations within the raw materials, the extruder or the printing atmosphere.

2.3 Regulatory Framework for Medical Device Manufacturing

While many industries only require the implementation of a Quality Management System (QMS) on an obligatory basis, the medical device industry is highly regulated and legislation requires medical device manufacturers and suppliers to have their QMS certified by a Notified Body (*REGULATION (EU) 2017/ 745 on Medical Devices*. European Parliament; Council of the European Union, 2017). This chapter reviews the regulatory requirements for quality assurance and quality control systems and the related requirements for manufacturing for the use case of personalized medical scaffolds. The markets considered are the European Union (EU) and the United States of America (USA), as these represent the largest markets with a unified regulatory framework. In the following, the legally binding regulations of both economic areas will be reviewed, as well as an internationally harmonized standard for quality management in medical technology.

The focus is intentionally placed exclusively on the relevant regulations for the manufacture of medical devices, after the product has already received the relevant approval. All requirements regarding the conformity assessment of the products themselves, as well as their clinical studies and approval processes, are neglected. Only the regulatory requirements that affect the production are considered. The regulatory requirements derived from the official documents are harmonized and categorized to be used for the design of suitable procedures and methods for quality assurance and quality control in Chapter 3.1.3 and thus form a relevant basis for the developed production infrastructure.

Legislation in the European Union

In the EU, products intended for marketing and utilization as medical devices are subject to the provisions of Regulation (EU) 2017/745, formally known as the European Medical Device Regulation (MDR). A pivotal aspect of this regulatory framework pertains to the mandatory implementation of a MDR compliant QMS (*REGULATION (EU) 2017/ 745 on Medical Devices*. European Parliament; Council of the European Union, 2017). Article 10 of the Regulation, “General obligations of manufacturers”, defines the requirements for manufacturers. The article refers to annexes that specify individual areas of requirements in more detail. Table 28 in Annex A.5 lists the requirements, organized into three distinct categories, in addition to the quality management system itself. The categories include product realization, which encompasses the manufacturing and testing process itself; technical documentation; and risk management.

Legislation in the United States of America

In the USA, the requirements for QMS for medical devices are regulated by the guideline 21 CFR Part 820 (QMSR, Quality Management System Regulation) from the Food and Drug Administration (FDA). Like the MDR, this is legally binding. The QMSR is also part of the Current Good Manufacturing Practice (CGMP) (*Quality System Regulation*. Food and Drug Administration, 2024). Table 29 in Annex A.6 shows an overview of the requirements of the QMSR that are relevant to this work.

International Quality Management Standards for Medical Devices

The standard DIN EN ISO 13485:2021 “Medical Devices – Quality Management Systems – Requirements for Regulatory Purposes” describes the requirements and implementation options for a QMS in medical technology that meets the standard defined by the EU and FDA but is partially less descriptive compared to the corresponding official documents. It serves as a voluntary measure for fulfilling the requirements of Regulation (EU) 2017/745 of April 5, 2017 on medical devices (Deutsches Institut für Normung e.V., 2021b). Table 30 in Annex A.7 shows an overview of the relevant requirements for QMS integration from the DIN EN ISO 13485:2021. The Overview shows that DIN EN ISO 13485:2021 combines the requirements of the MDR (Table 28) and the QMSR (Table 29). The standard DIN EN ISO/ASTM 52920:2023 “Principles of Qualification in Additive Manufacturing” is an established standard for the qualification of additive manufacturing processes but does not list any legal requirements (Deutsches Institut für Normung e.V., 2023). It can be used to supplement the ISO 13485 in order to define relevant measures for a quality management system specific for AM.

Harmonized Regulatory Requirements

The redundancies and discrepancies in the European and American legislation and in the international ISO 13485 can be harmonized by combining the requirements for each subject and by considering the more prescriptive requirement as the decisive one. Table 5 shows the identified requirement categories with corresponding references to the documents. The requirements for the definition of quality objectives are cataloged with the letter “Q”, requirements for product realization with “P”, requirements for technical documentation with “D” and requirements for risk management with “R”. Each requirement is described hereafter.

Table 5: Harmonization of regulatory requirements

	Requirements	MDR (EU) 2017/745	FDA 21 CFR Part 820	DIN EN ISO 13485:2021
Q1	General compliance	Art. 10 para. 9b		4.1.3, 8.4
Q2	Evaluation, selection and control of suppliers	Art. 10 para. 9d		7.4.1
Q3	Management of non-compliant products		90	8.3
Q4	Improvement, preventive and corrective measures	Art. 10 para. 9 l, m	100	8.1, 8.5
Q5	Statistical methods and sampling plans		250 A, B	7.5.6
P1	Permanent and complete identifiability		60, 65	7.5.8, 7.5.9
P2	Continuous monitoring of the compliance status		80C, 86	7.5.8, 7.5.9, 8.2.6
P3	Infrastructure	Annex I para. 10, 11	70 C, E	6.3, 6.4, 7.5.1
P4	Equipment and devices	Annex XI para. 7	70G, 72 A, B	7.5.1, 7.6
P5	Handling and storage		140, 150	7.5.11
P6	Verification of materials and information	Annex XI para. 6, 7	70H, 80B	7.3.8, 7.4.1, 7.4.3
P7	Process validation		75, 70I	7.5.6

P8	Process monitoring and control	Annex XI para. 4, 6	70A	7.5.1, 8.2.5
P9	Verification of the product	Annex XI para. 4, 6	80 D, E	7.5.1, 8.2.6
D1	Formal claims		180	4.2.5
D2	General documentation and procedures	Annex II para. 3-6	186	
D3	Product-specific documentation	Annex II para. 3, 4	181	
D4	Product history and proof of conformity	Annex II para. 3, 4	184	
R1	Identification and assessment of risks	Annex I para. 3, 10, 11		7.1
R2	Risk reduction measures	Annex I para. 4, 8		4.1.2

Q1: General Compliance

All measures that contribute to fulfilling the safety and performance requirements of the products must be implemented. The conformity and effectiveness of these measures must be proven.

Q2: Evaluation, Selection and Monitoring of Suppliers

Suppliers must be evaluated, selected and monitored according to specified criteria. Specifications, activities and results must be documented.

Q3: Management of Nonconforming Products

Products identified as nonconforming must be evaluated with subsequent rejection, disposal, justified special release or verified rework. Specifications, activities and results must be documented.

Q4: Improvement, Preventive and Corrective Actions

Measurements and analysis of all relevant data for continuous product and process improvement, as well as for the identification of actual and potential nonconformities must be monitored. Corrective and preventive actions to eliminate and prevent future nonconformities must be identified, validated, implemented and verified. Specifications, activities and results must be documented.

Q5: Statistical Procedures and Sampling Plans

Appropriate statistical methods for process validation, as well as control and verification of process capability and product conformity must be implemented. These must include appropriate sampling plans. Specifications must be documented.

P1: Permanent and Complete Identifiability

Unique identifiability of the product and its components before, during and after product realization must be guaranteed. Identifiers and components must be documented.

P2: Continuous Monitoring of the Conformity Status

The conformity status of a product during and after product realization must be identified and monitored. Activities and results must be documented.

P3: Infrastructure

The infrastructure must be qualified and regularly maintained according to defined requirements. Environmental control system to monitor and control the working environment, in particular the contamination by pollutants, microorganisms and particles must be regularly inspected. Specifications, activities and results must be documented.

P4: Equipment and Devices

Measurement and test equipment used in production must be qualified by regular maintenance, calibration, inspection and verification. Maintenance is carried out according to a maintenance plan. Calibration is carried out according to international standards and measurement standards or equivalent methods to meet specified limits for precision and accuracy. If the limit values are not met, an adjustment must be made and the quality of the products manufactured during the last calibration interval must be evaluated. Monitoring and measuring equipment must be protected against adjustment, damage and deterioration. Specifications, activities and results must be documented.

P5: Handling and Storage

Quality-reducing effects such as mix-ups, damage, expiration and contamination of products during handling and storage must be avoided. Specifications must be documented.

P6: Verification of Materials and Information

Release or disposal of incoming products and materials according to defined criteria must be verified. It must be ensured that the specifications of the development results do not exceed production capabilities. Specifications, activities and results must be documented.

P7: Process Validation

All processes whose results cannot be verified or are not verified must be validated. The validation also includes the qualification of the equipment and is carried out according to defined acceptance criteria and with appropriate statistical methods and sampling plans. Production and test processes (hardware and software) as well as the software of automated data processing systems must be validated. Specifications, activities and results must be documented.

P8: Process Monitoring and Control

Production processes must be monitored and controlled by monitoring and controlling process parameters and defined instructions to ensure and demonstrate product conformity and process effectiveness. Specifications, activities and results must be documented.

P9: Product Verification

Final product conformity must be inspected and verified. In addition to testing the product, a review of relevant production data must be conducted, along with a comparison of the measures and processes implemented with those intended. Specifications, activities and results must be documented.

D1: Formal Claims

The documentation must be legible and stored in such a way that it is easily identifiable and retrievable, and deterioration and loss are avoided. The documentation must show the conformity of the quality system and the products with the regulatory requirements, as well as the conformity of the products with the specified product requirements.

D2: General Documentation and Procedures

A Quality System Record (QSR) must be maintained, that includes non-product-specific procedures and documentation. This includes the reasoned selection, validation and verification of product testing methods, validation and monitoring of production processes, the results and solutions of risk management, and the standards, specifications and laws applied. Definition, activities and results subject to documentation requirements.

D3: Product-specific Documentation

For each product a Device Master Record (DMR) must be maintained, which describes the product characteristics and specifications, including safety and performance requirements, and defines the processes, equipment, parameters and environment for manufacturing and testing the product. It also contains the product-specific documentation and procedures if these differ from those of the QSR.

D4: Product History and Proof of Conformity

A Device History Record (DHR) must be kept for each manufactured product with product identification, production date, all process and test data, incl. components, as well as the conformity status with regard to the product requirements and the specifications of the device master record.

Note on Documentation:

The documentation must either contain the required information directly or refer to its location. Specifications are to be documented in the QSR if they are not product-specific and in the DMR if they are product-specific. Activities are to be documented in the QSR if they are not product-specific and in the DHR if they are product-specific. Results are to be documented in the QSR if they are not product-specific and in the DHR if they are product-specific.

R1: Identification and Assessment of Risks

Foreseeable hazards and risks must be identified and assessed, including those related to production and contamination control. Activities and results must be documented.

R2: Measures to Reduce Risk

Measures must be taken to reduce risk that correspond to the state of the art and an appropriate risk-benefit ratio. Processes that influence quality must be controlled on a risk basis. Specifications must be documented.

2.4 Production Infrastructure for Biomedical Applications

To meet the quality standards for the production of class III medical devices, a certified QMS according to EU Medical Device Regulation 2017/745 and ISO 13485 implies that an appropriate production environment is utilized. This is specified as an ISO Class 5 cleanroom.

The International Organization for Standardization (ISO) has established a comprehensive classification system, ISO 14644-1, for cleanrooms since 2001. This system, which includes nine classes ranging from ISO 9 to ISO 1, governs cleanroom cleanliness and has replaced the Federal 209E Standards. The ISO system determines the degree of cleanliness by defining the acceptable contamination levels, defined by particle count and size, as well as the requisite air change rates, contingent for each specific cleanroom's classification level (compare Annex A.8). Variables such as temperature, airflow, and humidity are also adjusted to the designated cleanroom class. The ISO is based on cumulative distributions of particle populations in the air ranging in size from $\geq 0,1 \mu\text{m}$ to $5 \mu\text{m}$ and is applicable to all industry sectors and applications, while the different classification system dependent on the utilization (ISO, 2015). Figure 14 shows the ISO classes and their typical areas of application.

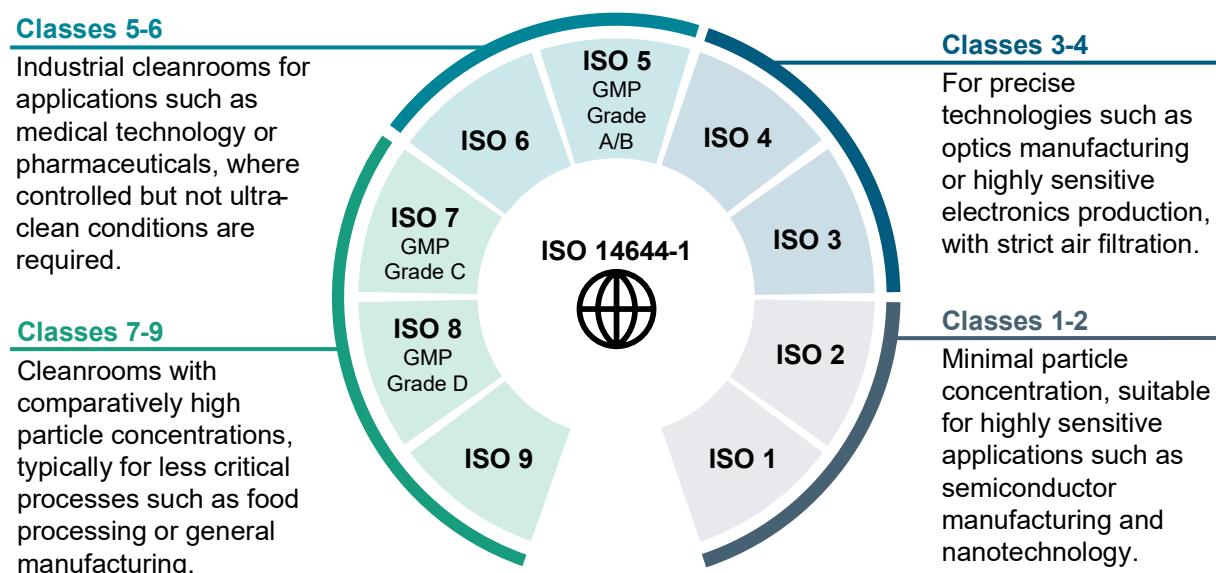


Figure 14: Cleanroom classes according to ISO 14644-1 (ISO, 2015)

The classification of cleanrooms using GMP grades (D-A) can be considered an extension for the medical technology pharmaceutical industry and, in addition to particle concentration, also takes into account microbiological requirements, for example, permissible colony-forming units (CFU) (Tanna et al., 2024). A cleanroom filters pollutants including dust, airborne microbes, and aerosol particles by directing air through a specialized filtration system (Gail, 2004). State of the art is the High Efficiency Particulate Air (HEPA) filter, which achieves 99,97 % efficiency in removing particles with a diameter of $0,3 \mu\text{m}$ or larger. The Ultra-Low Particulate Air (ULPA) filter removes particles between $0,1 \mu\text{m}$ and $0,3 \mu\text{m}$ with an efficiency of 99,999 %. These filters, function by purifying and decontaminating ambient air according to predefined requirements. The filtered air is then introduced into the controlled environment, where positive pressure generates airflow, thereby expelling contaminants produced by internal activities. The

contaminated air is subsequently either reintroduced to the ambient air or recirculated through the filtration system, restarting the purification process (John, 2013; Zhonglin, 2014).

When transitioning to the next stricter GMP grade, there must be a pressure increase of 10 Pa between the rooms to prevent less clean air from entering and contaminating the cleaner room. An increase of 15 Pa is recommended to prevent pressure loss when opening doors (ISPE, 2018; QPNotebook, 2016). Figure 15 shows a typical blueprint of a cleanroom facility with areas according to GMP grade D to A, which is based on recommendations of the International Society for Pharmaceutical Engineering (ISPE) and the World Health Organization (WHO) (ISPE, 2018; WHO, 2006).

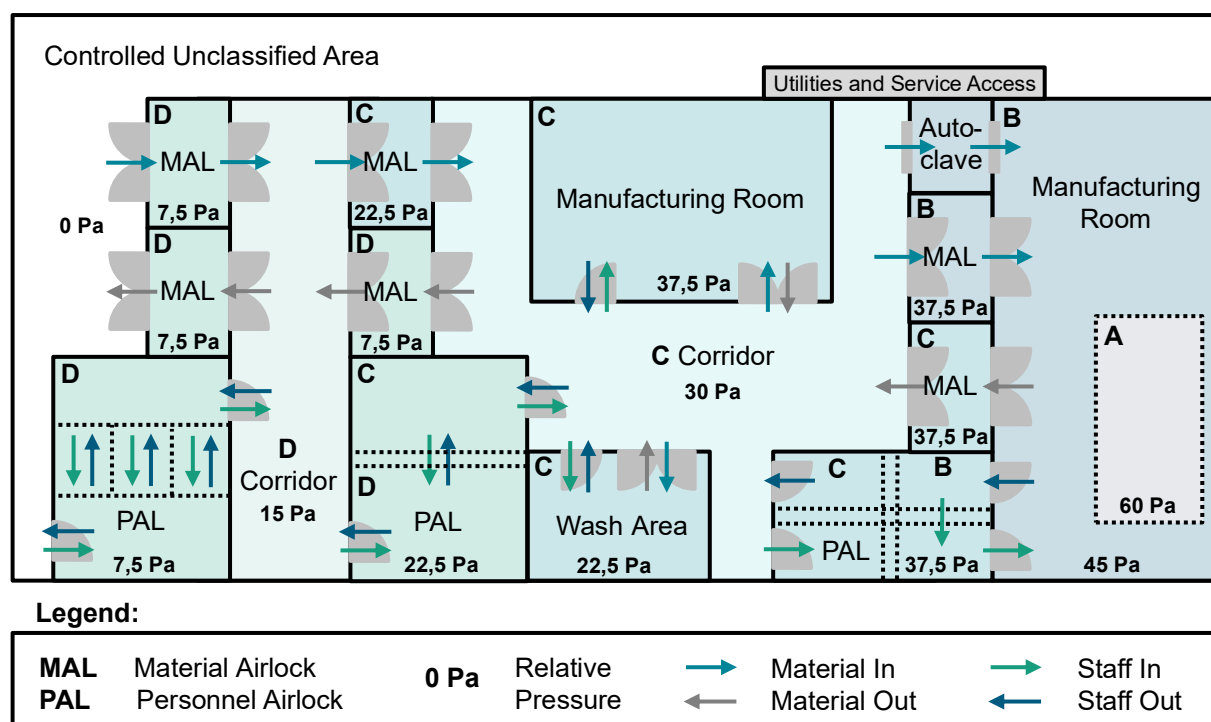


Figure 15: Exemplary cleanroom blueprint for GMP grades A to D (QPNotebook, 2016)

Grade D cleanrooms are generally only used for tasks such as cleaning and storage of cleaned equipment and accessories prior to sterilization. For the transition to the Grade C cleanroom, unidirectional material airlocks (MAL) and personnel airlocks (PAL) are used to prevent cross-contamination. In Grade C areas, lower-risk steps for sterile product manufacturing can be carried out. These include, for example, sterile packaging and assembly processes or quality control steps. All aseptic process steps are prepared in the Grade B cleanroom. At the same time, a B zone is the necessary environment for a Grade A cleanroom, where sterile products can be handled aseptically, while being exposed to the atmosphere (ISPE, 2018; WHO, 2006).

In terms of EAM-based production of polymer-based medical scaffolds, a Grade A cleanroom is necessary because the implants must be manufactured openly and aseptically are usually not sterilized before use. In general, each application must be individually assessed for risk to determine which processes can be carried out in which cleanroom zones.

2.5 Decoupled Production and Multi-agent Path Finding

Decoupled production is a production logistics approach in which the individual production processes or stations are not connected in a fixed sequence. The production stations are not rigidly linked to each other but can work flexibly and independently. Production can therefore take place in varying sequences, without a specific order having to be strictly adhered to. This approach has the advantage of enabling greater flexibility and adaptability to change. For example, production capacities can be better aligned with fluctuations in demand or different product types. This contrasts with conventional chained production, in which the individual production stations are connected in a fixed, linear sequence, like on a conveyor belt (Brecher, 2012; Göppert et al., 2018; Hu et al., 2011). Figure 16 illustrates the difference between these two approaches.

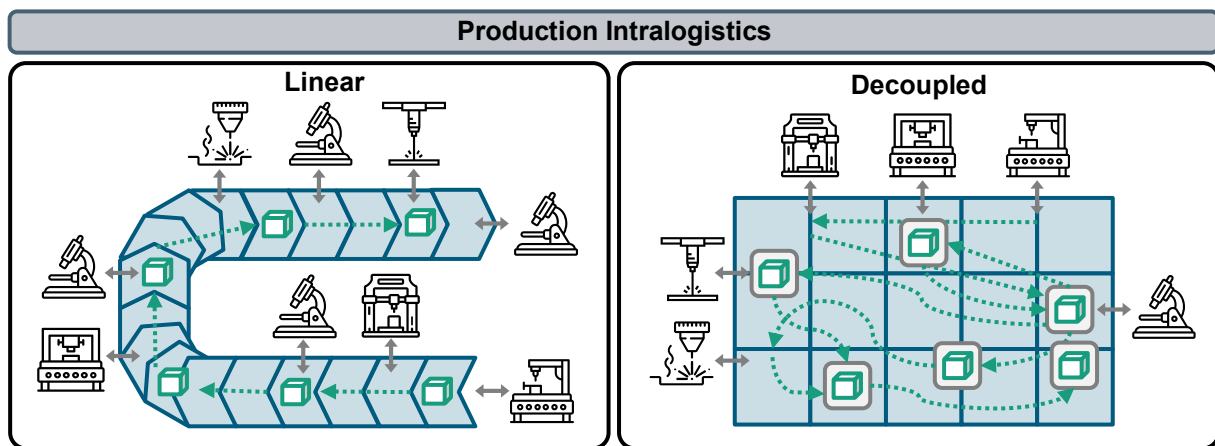


Figure 16: Schematic comparison of linear production chains on a conveyor belt and decoupled flexible production intralogistics with multiple independent transportation agents on a planar drive system

The approach of decoupled production, also known as line-less production or freely interconnected production, has its origins in assembly technology (Brecher et al., 2017). A line-less assembly system is defined as one that provides each individual product with its own job route without spatial or temporal restrictions (Göppert et al., 2018). A job route is defined for each individual order, so that different job routes may exist for multiple orders of a product type depending on the available assembly resources. This makes it possible to control different assembly resources for different variants, to switch to alternative assembly resources when the original ones are occupied, and to integrate further assembly resources without taking the spatial sequence into account. This flexibility enables the assembly system to be reconfigured without interruption and to be scaled without the effort of holistic reconstruction. Furthermore, the flexible routing enables to increase the utilization of the assembly resource. To use this potential and optimize the resource utilization, the implementation of a decoupled production system requires the solving of a multi-criteria optimization problem. These problems are characterized by dynamic changes in the process step sequence, the process steps locations and the process steps execution times (Hüttemann et al., 2017).

For the planning of individual job routes, a control system is necessary. This uses product information and production management information from an Enterprise Resource Planning

(ERP) system or other IT systems, as well as status information from the production machines. As visualized in Figure 17, job route planning is divided into the steps of matching (1), for determining possible routes for a job, and routing (2), for determining a specific route for a job (Göppert et al., 2018).

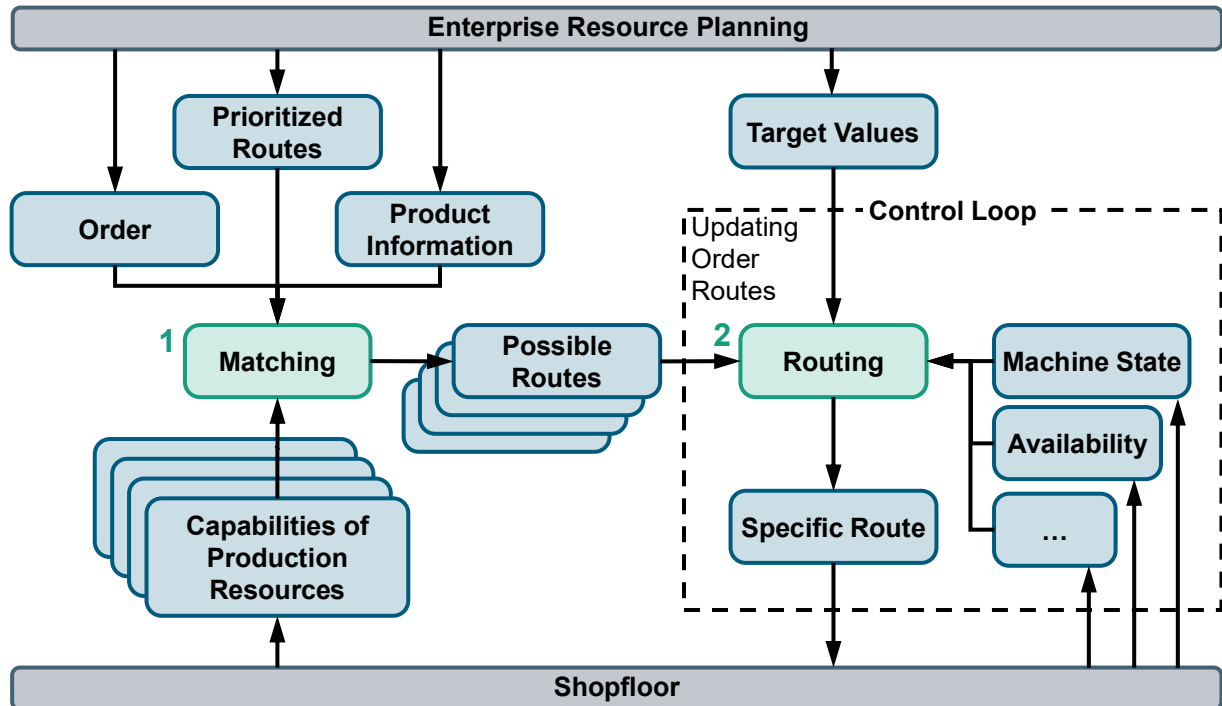


Figure 17: Control structure for decoupled production systems (Göppert et al., 2018)

In addition to the information coming from the ERP system, the capabilities of the production resources on the shopfloor are considered in the matching process in order to identify suitable paths for the transportation agents. In the routing process, real-time data on machine status and availability, as well as defined target values, such as manufacturing process sequences, are used to determine specific routes, which are then transferred to the transportation agents on the shop floor (Göppert et al., 2018). While the matching process is usually determined by predefined process parameters or company specifications, for the routing step, different control loops and algorithms can be implemented for path planning.

Multi-agent Path Finding

For the case that multiple transport agents are active, for example in the form of mobile robots on a shopfloor or movers on a planar drive system, the multi-agent path finding (MAPF) is relevant. MAPF is a computational problem that involves planning collision-free paths for multiple agents, each aiming to reach a designated target while avoiding collisions with both static obstacles and other agents. The objective is to minimize the sum of their travel times, the makespan, or other optimization criteria (Stern et al., 2019; Yu, 2016). The fundamentals of the mathematical description of MAPF problems, as presented in detail by Stern et al., are not provided in this work; instead, the application of MAPF solvers is focused.

The range of possible MAPF problems is divided into classical and non-classical MAPF. Classical MAPF is mathematically clearly describable, while non-classical MAPF involves additional conditions, such as temporary constraints, heterogeneous agents, or agent task assignments. This increases the relevance for real applications, but also reduces the usability of several MAPF solvers, which is why in practice usually the attempt is made to generalize a non-classical MAPF problem into a classical MAPF problem (Gao et al., 2024). Figure 18 provides a state-of-the-art overview of established MAPF solver.

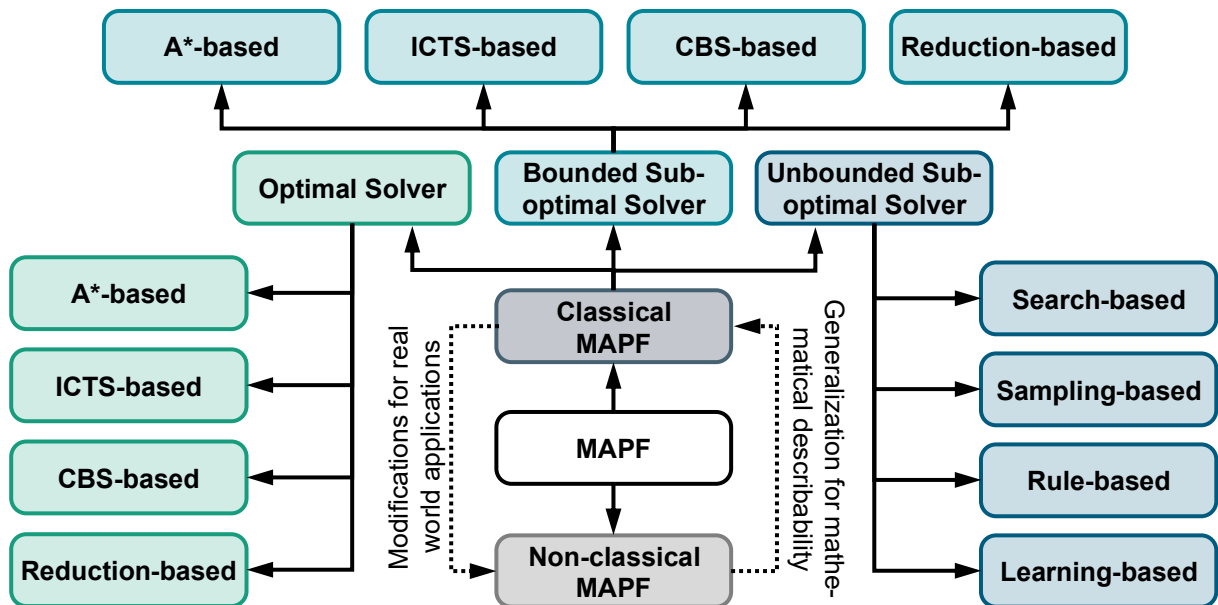


Figure 18: Overview of classical MAPF solvers (Gao et al., 2024)

The solvers are broadly categorized into optimal and sub-optimal algorithms. Sub-optimal algorithms are further categorized into bounded and unbounded solvers.

Optimal algorithms guarantee the shortest possible paths for all agents without collisions but are computationally intensive. Examples include centralized algorithms based on Conflict-based Search (CBS) or Increasing Cost Tree Search (ICTS). Finding an optimal solution for classical MAPF, depending on the complexity and number of agents, can lead to computing times that are impractical for real-world applications (Gao et al., 2024; Yu, 2016).

Sub-optimal algorithms aim to find practical solutions that are not necessarily the most efficient regarding to time and path length but are computationally less expensive. Sub-optimal solvers can be based on the same strategy as optimal solvers like CBS but are extended by a restrictive component, for example Priority-based Search (PBS) or Multi-Agent Rapidly-exploring Random Tree (RRT). Unbounded sub-optimal solvers can include rule-based or learning-based approaches, to improve speed by using decoupled methods or admissible heuristics, although they do not guarantee completeness. New developments in machine learning and deep learning for algorithm optimization are currently subject of research (Farhadi et al., 2025; Gao et al., 2024). Figure 19 visualizes the feasible solution space for MAPF solvers and the associated trade-off between multi-dimensional quality criteria, such as time and path efficiency, and the computation time required to find a solution. Gao et al. provides a

comprehensive review of all established MAPF solvers, which can be used to access information on the structure and functioning of the individual algorithms.

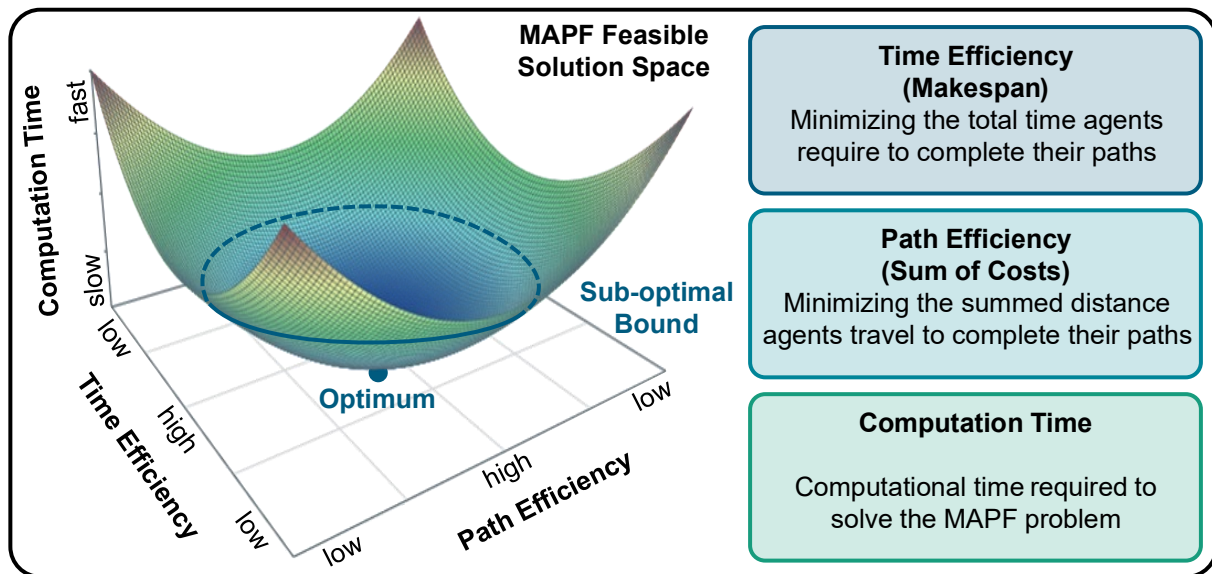


Figure 19: Visualization of the trade-off of solution quality and computation time between optimal and sub-optimal classical MAPF solvers (Gao et al., 2024).

Depending on the selected scenario and its requirements, it is necessary to consider which type of solver is suitable. For MAPF applications in logistics and production, sub-optimal solvers are most prevalent (Gao et al., 2024; Liu et al., 2024). These solvers are often based on a modified CBS strategy, which will be described in the following.

Conflict-based Search

The CBS algorithm works on two levels: a high-level search that identifies conflicts and resolves them by means of restrictions, and a low-level search that calculates an optimal path for each agent. In the high-level search, CBS starts with conflict-free planning by calculating the shortest path for each agent separately. If conflicts arise – for example, if two agents reach the same position at the same time – the problem is split into two sub-problems. One agent receives the restriction that he is not allowed to enter the problematic position at that time, while the other receives an alternative restriction. These sub-problems are recursively examined further until a completely conflict-free solution is found. The low-level search considers the specific route planning of the agents. CBS is particularly suitable for small to medium-sized scenarios in which optimal paths are required, for example in production intralogistics with a limited number of transport robots. Since the number of conflicts can increase exponentially with the number of agents, CBS is less efficient for large and complex problems. In such cases, extensions such as Improved CBS (ICBS) are often used to enable a sub-optimal but faster solution (Sharon et al., 2015; Stern, 2019).

2.6 Digital Production Modeling

The ongoing digitalization of industrial production is leading to an increased use of digital representations of physical systems. The three main concepts Digital Twin, Digital Shadow and Digital Model must be distinguished, as shown in Figure 20. A digital model is a static digital representation of a physical system that is used primarily for simulation and analysis. There is no automatic feedback between the physical and digital systems. A digital shadow is an advanced form in which data from the real world is automatically transferred to the digital image, but without mutual interaction. The digital twin is a bidirectional, dynamic coupling between the physical and digital systems that makes it possible not only to transfer data from reality into the model, but also to implement decisions and optimizations from the digital twin back into the physical system (Kritzinger et al., 2018; Fuller et al., 2020; Michael et al., 2023).

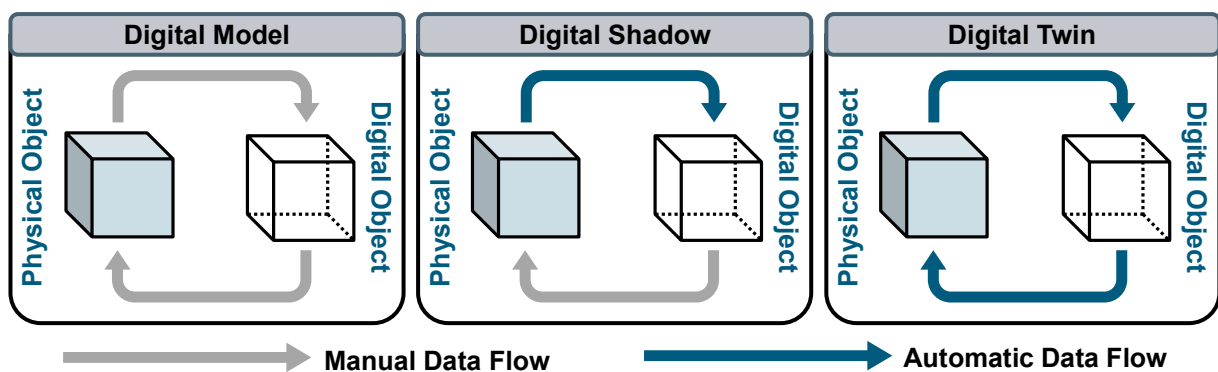


Figure 20: Digital Twin levels according to the ability to exchange data (Fuller et al., 2020)

In production technology, digital models are of particular importance for planning and optimization purposes. By modeling production chains or entire production infrastructures, simulations of manufacturing scenarios can be conducted that would be too costly to carry out in practice. This makes it possible to efficiently optimize, for example, scheduling or shopfloor layouts (Chen et al., 2020; Koulouris et al., 2021). In general, literature categorizes simulation methods and their underlying models into different classes, which are illustrated in Figure 21.

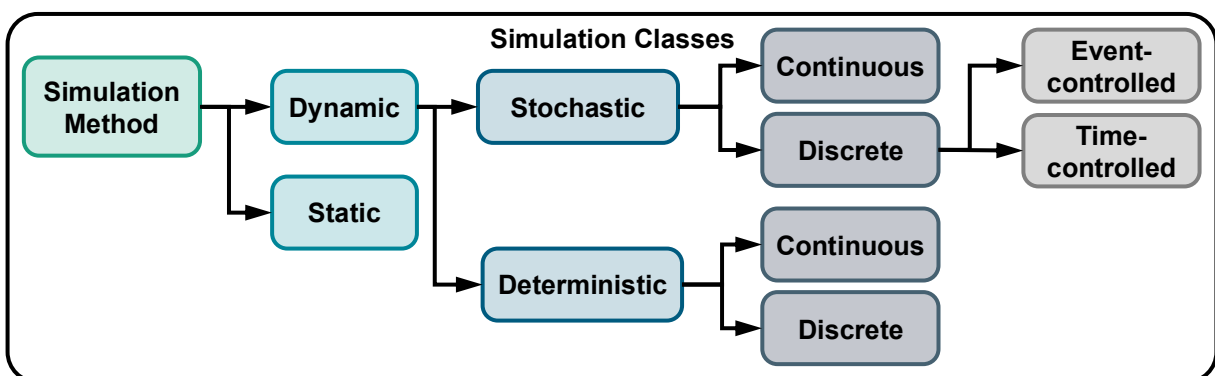


Figure 21: Classification overview of simulation methods (Spindler et al., 2021)

Fundamentally, a distinction is made between dynamic and static models, with dynamic models considering the change over time and static models neglecting the influence of time. In the following, dynamic models are considered. A distinction is made between stochastic and

deterministic models. Deterministic models differ from stochastic models in the way they represent random behavior. It is assumed that no random changes occur within a deterministic model. In stochastic models, the behavior of the model in terms of changed initial conditions is not clearly predictable. Changes in state can only be described with probabilities. Another distinction between the models is made regarding the modeling of time. In continuous models, the model changes continuously over time, while in discrete models it only changes at certain points in time (Carlo et al., 2014; Spindler et al., 2021).

Discrete-event Simulation

Discrete-event simulation (DES) is the simulation method most often used to analyze production processes. The method was initially used in the fields of operations research and industrial engineering, but today it is used for a wide range of simulations, such as in the transport or healthcare sector. DES is a simulation method based on a discrete model, which usually exhibits stochastic behavior. In contrast to time-controlled simulations, DES does not use constant time increments to determine whether changes in the system state have occurred. Instead, state changes are only recorded when an event occurs. Accordingly, time does not progress in constant but in variable time increments. The length of the time increments is determined by the time between two events (Galvão Scheidegger et al., 2018; Gutenschwager et al., 2017).

In DES, a system is described in terms of entities, attributes, activities, events, and states, compare Figure 22. In a production system, entities can be, for example, machines or manufactured parts. Attributes describe the properties of these entities. Activities include operations performed with the entities. Events are occurrences such as the arrival of a product. States indicate for example, whether a machine is currently in use or not (Banks et al., 2013).

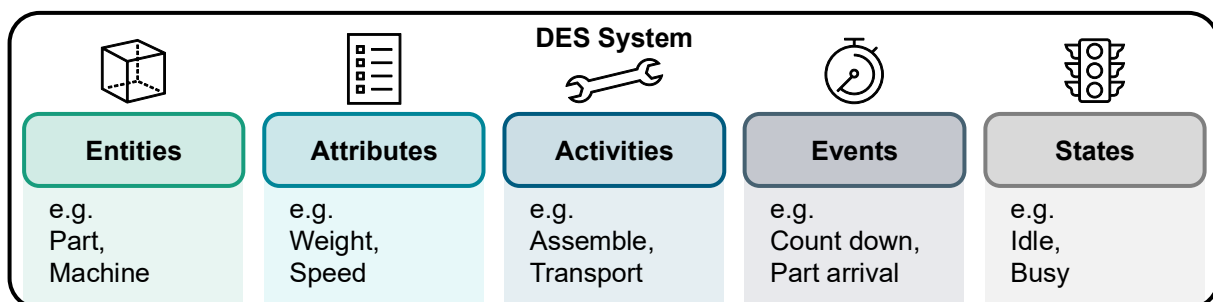


Figure 22: DES system components (Banks et al., 2013)

The basic concept of DES states that every event occurs at a specific point in time. These events are processed chronologically based on an event list, whereby the simulation clock jumps to the respectively next listed event. In addition to these scheduled events, also known as booked events (B-events), there are also conditional events (C-events) where the execution time is not known but is triggered by a fulfilled condition. The lists of B- and C-events are then run through circularly and, depending on the activity triggered by the event, the states or attributes of individual entities are changed. The simulation is ended as soon as the event lists are empty, the predefined simulation duration is reached or a set condition determines the end of the simulation (Gutenschwager et al., 2017; Robinson, 2014).

Production Simulation and Key Performance Indicators

From an economic point of view, simulating a production environment is a valuable method of obtaining data for decision-making regarding new investments or restructuring. To quantify and compare production performance, it is useful to track or calculate key performance indicators (KPI) within a production simulation. The ISO/DIS 22400-2:2014 norm defines established KPIs for manufacturing operations management (ISO, 2023). Some of these KPI, applicable for fully automated personalized scaffold production, are introduced in Table 6.

Table 6: Production KPIs according to ISO/DIS 22400-2

Content	Key Performance Indicator
1	Throughput Rate
Description	Process performance in terms of produced quantity (PQ) of an order and the actual execution time of an order (AOET)
Formula	$Throughput\ Rate = PQ/AOET$
Range	0 – ∞ quantity units / time unit
2	Utilization Efficiency
Description	The utilization efficiency is the ratio between the actual production time (APT) and the actual unit busy time (AUBT)
Formula	$Utilization\ Efficiency = APT/AUBT$
Range	0 % – 100 %
3	Availability
Description	Availability is a ratio that shows the relation between the actual production time (APT) and the planned busy time (PBT) for a work unit.
Formula	$Availability = APT/PBT$
Range	0 % – 100 %
4	Effectiveness
Description	Effectiveness represents the relationship between the planned target cycle and the actual cycle expressed as the planned runtime per item (PRI) multiplied by the produced quantity (PQ) divided by the actual production time (APT).
Formula	$Effectiveness = PRI \cdot PQ/APT$
Range	0 % – 100 %
5	Quality Ratio
Description	The quality ratio is the relationship between the good quantity (GQ) and the produced quantity (PQ).
Formula	$Quality\ ratio = GQ/PQ$
Range	0 % – 100 %
6	Overall equipment effectiveness index (OEE)

Description	The OEE index represents the availability of a work unit (3), the effectiveness of the work unit (4), and the quality ratio (5) KPIs integrated in a single indicator.
Formula	$OEE = Availability \cdot Effectiveness \cdot Quality\ Ratio$
Range	0 % – 100 %
7	First Pass Yield (FPY)
Description	The first pass yield (FPY) designates the percentage of products, which full fill the quality requirements in the first process run without reworks (good parts). It is expressed as the ratio between good parts (GP) and inspected parts (IP).
Formula	$FPY = GP/IP$
Range	0 % – 100 %
8	Process Capability Index (C_p)
Description	The process capability index (C_p) is the relationship between the dispersion of a process and the specification limits. The method compares the range between the upper or lower specification limits (USL, LSL) and the 6σ process dispersion for a specific characteristic.
Formula	$C_p = (USL - LSL)/(6 \cdot \hat{\sigma})$
Range	0 – ∞ (A process is usually called capable if the $C_p > 1,33$)
9	Critical Process Capability Index (C_{pk})
Description	The critical process capability index (C_{pk}) is the relationship between the dispersion of a process and the USL or LSL and its average of averages ($\bar{x}$). The method compares the range between the upper or lower specification limit and its averages and the 3σ process dispersion.
Formula	$C_{pku} = (USL - \bar{x})/(3 \cdot \hat{\sigma}); C_{pkl} = (\bar{x} - LSL)/(3 \cdot \hat{\sigma})$ $C_{pk} = \min(C_{pku}, C_{pkl})$
Range	0 – ∞ (A process is usually called capable if the $C_{pk} > 1,33$)

Interim Conclusion

In this chapter, problem- and application-relevant theories, hypotheses and legislations from the current state of the art are collected and complete step (B) of the research process according to Ulrich, compare Figure 5 (Ulrich and Hill, 1976). In the following two main chapters of this thesis, the research process is continued with steps (C), (D) and (E).

3 Development of the Production Infrastructure

The development approach for the production system design is based on the established VDI Guideline 2221:2019 (VDI, 1997). The overall methodology, which is presented in Figure 23 and Figure 24, is structured into multiple sub-methods, which are applied and explained within the following chapters. The corresponding chapters that address these sub-methods are indicated by the numbering in the figures.

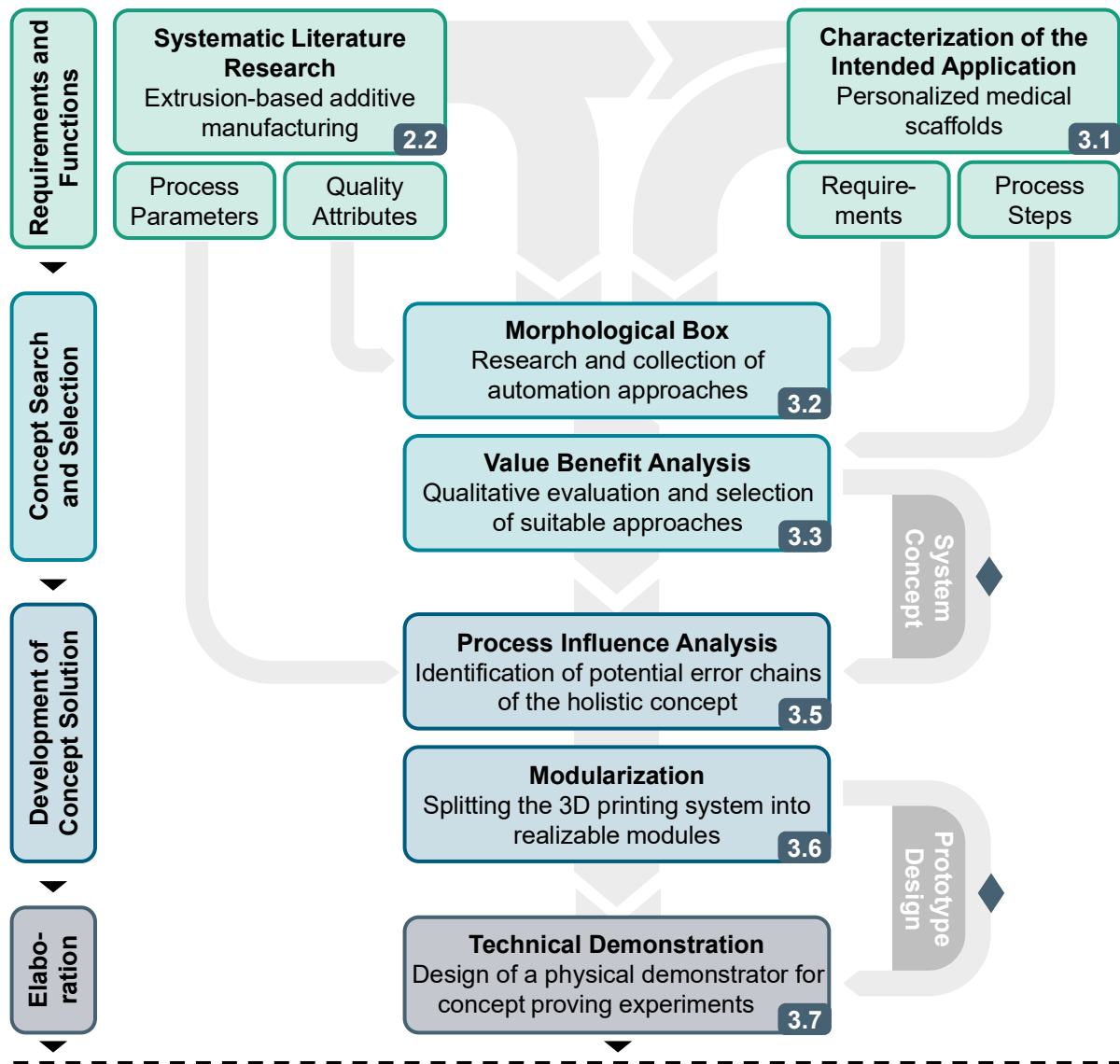


Figure 23: Methodology for technical concept development, oriented according to VDI Guideline 2221

The systematic literature research to identify relevant PP and QA serves as a basis for the subsequent characterization of the intended application, resulting in defined process steps and requirements. For the realization of the functions of the individual process steps while meeting the requirements, concepts are sought and selected. The morphological box method and the value benefit analysis are used for this purpose, which results in a holistic system concept for

the production infrastructure. The concept is analyzed in terms of its influence on process parameters and is further refined in a modular approach, resulting in a prototype design. This is elaborated into a demonstrator to validate the main technical properties of the production system. These steps conclude the main development process of the concept for a scalable production infrastructure for EAM-based personalized medical scaffolds.

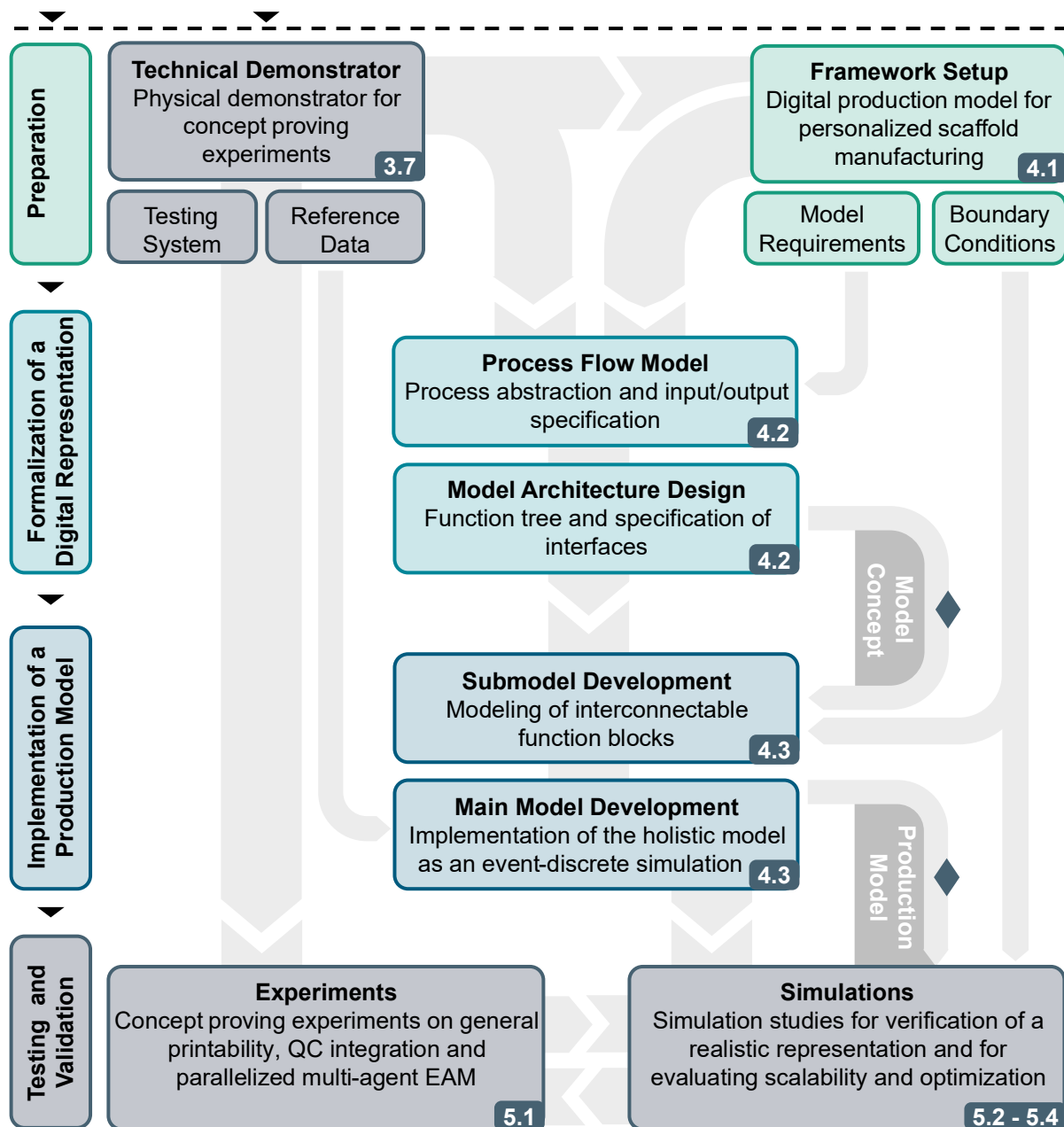


Figure 24: Extension of the concept development methodology to include a digital representation of the developed production system with subsequent validation

In addition to the design of a dedicated production infrastructure, further research focus is on the digital representation of such a production. Therefore, Figure 24 illustrates the methodological approach. The development of this digital model is divided into three main steps, Preparation, Formalization and Implementation, and is addressed in detail in Chapter 4.

To validate the developed production infrastructure, physical experiments are carried out on the demonstrator to prove the general functional suitability of the production concept with regard to the main technical features. On the other hand, the digital model is used to validate the production infrastructure in terms of its scalability. For this purpose, several simulation studies are carried out. The validity of the digital model itself is verified by comparing it with the physical demonstrator and by proving the accurate representation of reality. These experiments and simulations are addressed in detail in Chapter 5.

The results of this chapter have already been published in a shortened form in the author's previous article entitled "Development of an End-to-End Automated Production Concept for Extrusion-based Additive Manufacturing of Personalized Medical Scaffolds" (Janning et al., 2025). Previously published figures are marked with the corresponding citation.

3.1 Process Characterization

In this chapter, the production process is characterized in order to develop a solution that meets the requirements. For this purpose, the automated production is described in abstract terms and the use case is specified. Basic technical process requirements are specified, and the critical process parameters and quality attributes are defined. Finally, performance criteria are determined, which are then relevant for the search for automation solutions.

This work focuses on the EAM technology for medical applications, in particular on the research gap in terms of automation and scalability as derived in Chapter 1.2. The literature review provided a detailed description of the technology's functionality and its process steps. Accordingly, an automation cycle can be drafted in a generalized form, as shown in Figure 25.

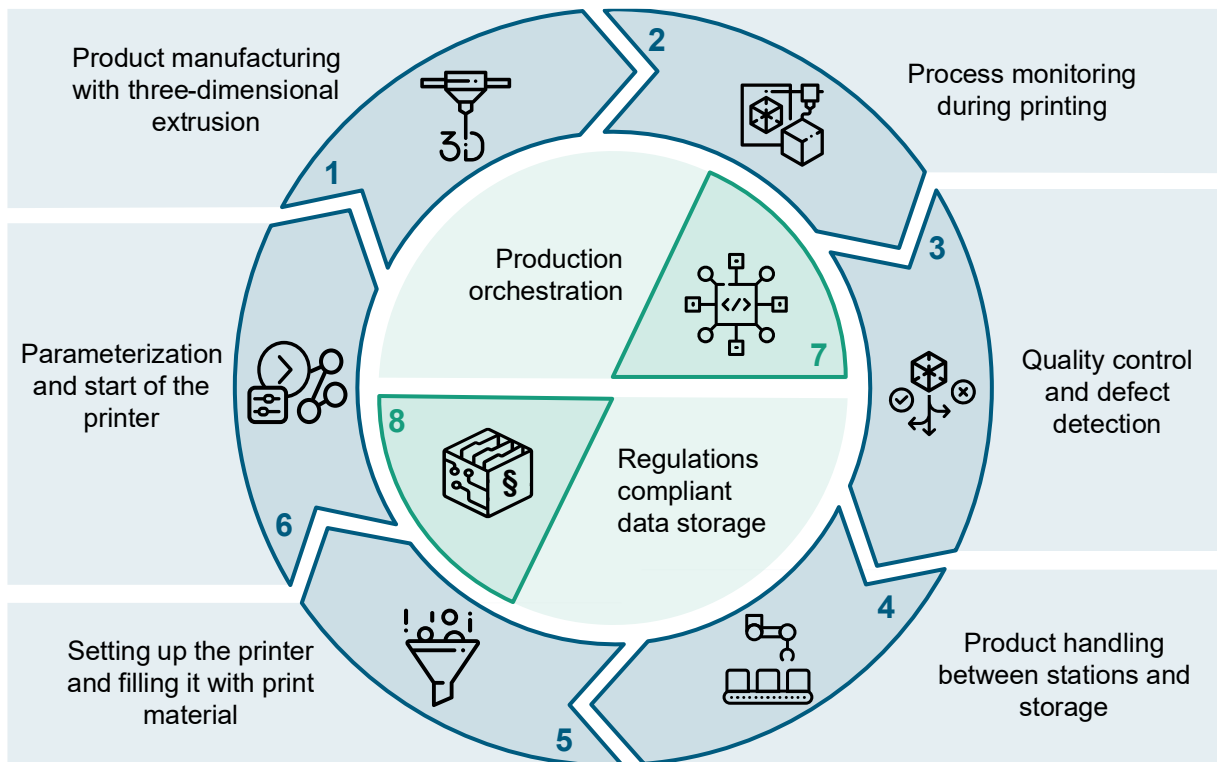


Figure 25: Generalized automation cycle for EAM

The extrusion process (1), considered in isolation, is by design performed automatically, so that the modification of the extruder itself is not an objective of the following development. Monitoring the printing process (2) can be realized with various technologies but is also still a subject of current research. Concepts for monitoring relevant process parameters are being developed. The control of the quality of the printed objects (3) also offers various application-dependent approaches, which are evaluated in this work. Product handling (4), including production intralogistics, product and material storage, and the removal of objects from the printing bed, are processes that hold potential for optimization in terms of automation and scalability. These processes are examined in detail in the following. Printer set-up and filling with material (5) continues the automation cycle and is completed on the digital level by the re-parameterization for the next print job and the corresponding re-start of the process (6). To enable holistic automation, the orchestration of the relevant production subsystems is necessary (7).

Technical solutions for this already exist but must be adapted for the corresponding automation concept. Particularly relevant for the medical application, compliant data handling is relevant for the automation of the process (8). For this, reference is made to the corresponding legislations and the resulting requirements, which were presented in Chapter 2.3. Based on this general process description, for a complete characterization, the use case is further refined in the following.

Use Case Specification

In order to be able to develop a practical concept and to carry out a use case-based validation, the raw material, fabrication process and product category are defined as shown in Figure 26. PCL is chosen as the raw material in a granular form. This synthetic polymer has been established for many years for medical applications, in particular as a suture or implant material (Nguyen et al., 2023; Soufivand et al., 2020; Xu and Ivanovski, 2025). FGF is chosen for its ability to process pellets as raw material and does not require preprocessing into filaments. In addition, there are established FGF extruders that meet hygienic design standards (Justino Netto et al., 2021; Nguyen et al., 2023). Tissue reconstruction scaffolds (Figure 1, (4) and (5)) are selected because they represent a significant market share among personalized medical products (Grand View Research, 2022).

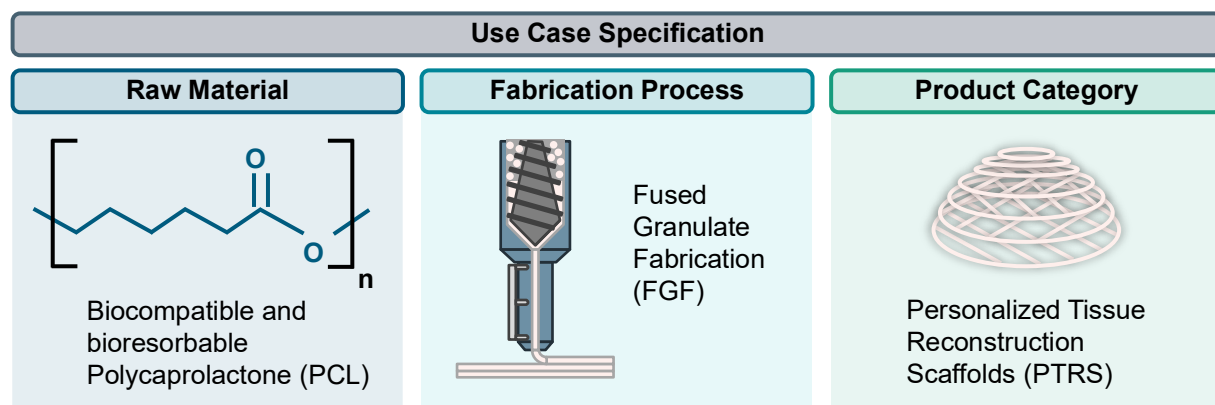


Figure 26: Specification of the use case on FGF of PCL-based PTRS (Janning et al., 2025)

3.1.1 Basic Process Requirements

While the 3D printing process itself is automated, the other steps like quality control or material handling and logistics, are dominantly manual. In the following, the manual process steps, derived from reviewing literature, are described and the requirements for the transfer into automated production are defined. The process steps relevant in this context are broken down into their main functions, as shown in Figure 27.

Material Supply and Processing

At the beginning of the printing process, PCL granulate is provided to the extruder. This process step includes three subfunctions. First, sufficient quantities of the raw material must be stored under controlled environmental conditions. Due to the hydrophilicity of PCL, it must be stored in a cool ($<5\text{ }^{\circ}\text{C}$) and low-humidity place to prevent moisture absorption, and in a dark and closed vessel to prevent premature degradation. The granules are transported from storage to the extruders granulate reservoir, from where they are transferred to the hot end and melted for product forming. The granules should not remain in the uncooled extruder reservoir for more than two weeks, as otherwise, properties may change due to degradation. The product shaping is realized with an extruder forcing the melted polymer through a nozzle. This requires the synchronous control of the nozzle temperature, the extrusion rate and the three mechanical axes as well as optionally further vents for cooling the printed layer.

Quality Control

The necessary quality controls for medical devices, derived in Chapter 2.3, are divided into pre-production, in-production and post-production steps. Before production, for example, incoming material inspections or, in general, the validation of the individual processes is necessary. These are covered by the manufacturer's quality assurance system. Post-production controls can include randomized 100 % inspections, which for example include destructive mechanical testing. For the design of the production infrastructure within this work, only the in-production quality controls are considered. These are divided into two categories:

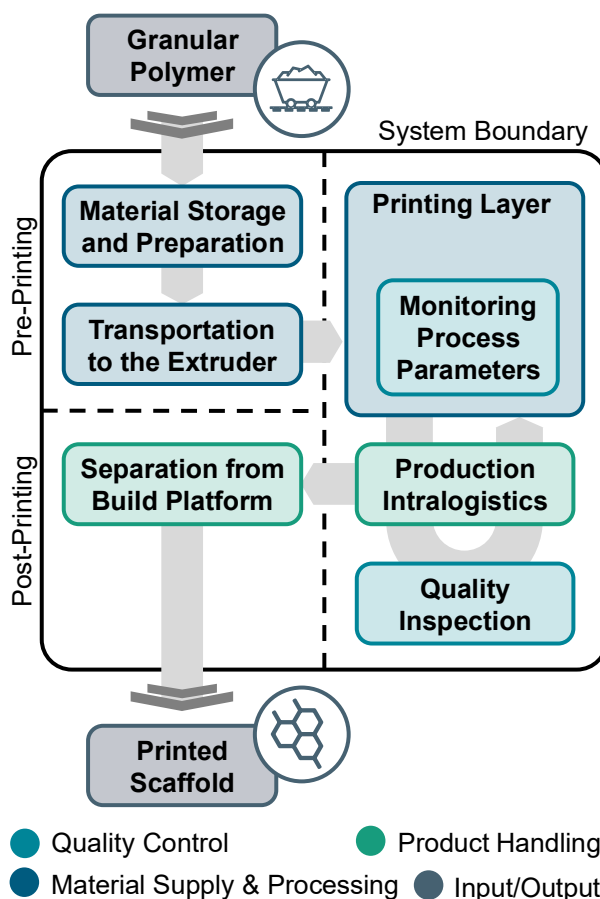


Figure 27: Basic overview of the individual process steps and their main functions from incoming material supply to outgoing finished products (Janning et al., 2025)

1. Monitoring critical process parameters: Process parameters need to be recorded and documented for each product. For the specified use case this includes extrusion rate and extrusion temperature.
2. Verifying critical quality attributes: The attributes of each product need to be verified. For the specified use case dimensional accuracy of the printed layers, the porosity of the scaffold and the linkage between the layers are controlled. Therefore, tolerable thresholds must be defined for these attributes. The measured data is used for documentation, quality assessment and process adjustments.

Product Handling

Product handling describes the transport of the components between workstations. This includes transporting the printed object from the extruder to the quality control stations, storing the printed product in a storage area, and handling the substrate plates on which the product is printed. Due to the scalability and efficient resource utilization, specific stations within the whole system are to be used in parallel for multiple products if they only account for a small proportion of the total production time. This particularly affects the quality inspection with its often expensive metrology, as well as the separation stations, which are required once at the end of each printing process. Once a product is completed, it is separated from the build platform and transported to the designated storage location where it can be received by employees. This exceeds the system boundary shown in Figure 27.

In addition, it must be possible to remove faulty objects, which have failed one of the quality controls and restart the same print job subsequently. Removing the product from the build platform can be a critical step, as this is where damage can be done to the product after the end of the printing process (Glatt et al., 2021).

Based on the characterization of the intended application and the hereby described basic technical requirements, the associated functions are summarized in a function tree, shown in Figure 28, allowing the design and development to be more focused (Romli et al., 2013). The function tree helps to structure the main functions into more granular subfunctions. These are then transferred to the morphological box as characteristics. The subfunctions are used to form search criteria for the exploratory literature research to find a suitable solution concepts.

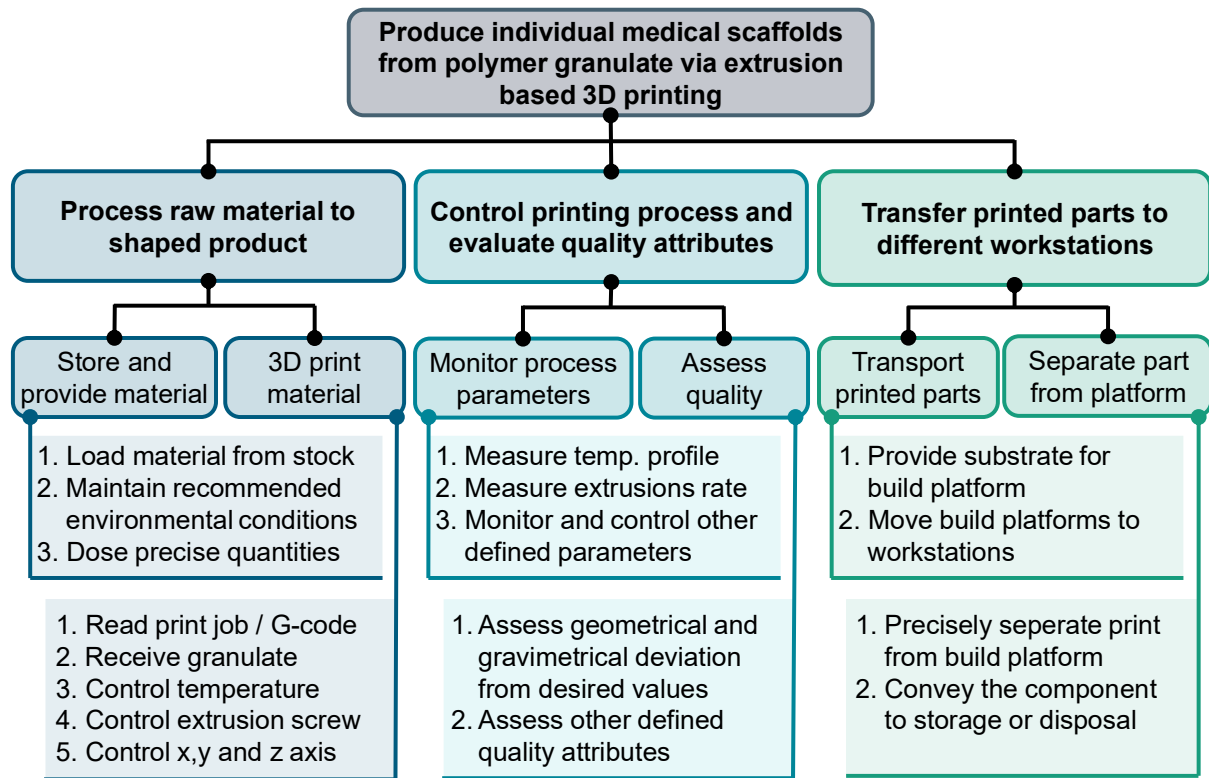


Figure 28: Function tree for the automated production of individual medical scaffolds using EAM (Janning et al., 2025)

3.1.2 Critical Process Parameters and Critical Quality Attributes

Depending on the specified use case only some of the identified parameters and attributes from Chapter 2.2.3 can be defined as a Critical Process Parameter (CPP) or a Critical Quality Attribute (CQA). The most frequently mentioned process parameter, deposition speed, is a parameter that can be specifically set via the 3D printer control system so that no additional monitoring is necessary. The extrusion pressure and the extrusion rate both refer to the extruded volume flow of molten polymer. The second most often mentioned process parameter is the extrusion temperature, which should therefore be monitored in this application. All other parameters shown in Figure 10 are either defined by the product or are set once in the system, such as the nozzle diameter, deposition speed, platform temperature and cool down time. While they must be validated once before production, they do not need to be monitored continuously. Others, such as the ambient temperature and humidity are monitored by the clean-room system itself and do not require additional metrology. Table 7 highlights the process parameters critical for the specified application.

The quality attributes of the products to be manufactured, are divided into biomedical, mechanical, and geometrical attributes. Biomedical properties such as cell viability and cell growth are not relevant for the defined cell-free use case. The other biological properties like biocompatibility and biodegradability are influenced solely by the choice of material and the given geometry of the product, so that no process is necessary to control these attributes in production. The dimensional accuracy and the porosity of the finished product influence its functionality and safety and thus are critical quality attributes, requiring these to be monitored during production. The mechanical properties, such as the load capacities and the fatigue strength, derive from the connection of the individual filaments between the layers in the scaffold application. This layer bonding should be monitored during the production process. It is not possible to control the mechanical properties using compression or tensile tests, as the products are personalized scaffolds with inherently different geometries for which no target values for mechanical strength can be specified. The surface roughness attribute is not relevant for the scaffold application due to the intention of a porous surface.

Table 7: Process parameters and quality attributes classified as relevant for the use case (CPPs and CQAs are marked in bold)

Process Parameter	Abbreviation	Unit	Relevance
Nozzle Diameter	d_{Nozzle}	mm	Predetermined by the component used, therefore not a CPP that could be monitored. A suitable nozzle diameter should be determined experimentally and then validated once for each material used.
Extrusion Rate	V'_{Ex}	ml/s	The extrusion rate influences several quality attributes like dimensional accuracy and mechanical strength and should therefore be monitored. It is categorized as a CPP.

Deposition Speed	v_{Mover}	m/s	Can influence print quality, but it is predefined in the system and does not need to be monitored. A one-time validation is sufficient.
Extrusion Temperature	T_{Nozzle}	°C	Can have a major influence on the cross-linking of the individual layers and thus on the mechanical properties. It is categorized as a CPP.
Platform Temperature	$T_{Platform}$	°C	Can influence print quality, but it is predefined in the system and does not need to be monitored. A one-time validation is sufficient.
Ambient Temperature	$T_{Ambient}$	°C	Can influence mechanical properties but is defined and controlled by the clean room itself.
Ambient Humidity	$H_{Ambient}$	%	Can affect biodegradability and influence mechanical properties but is defined and controlled by the clean room itself.
Cool Down Time	t_{Cool}	s	Must be defined depending on the use case and is predefined for the production system. Exceeding the values is not critical, but falling short can affect the mechanical properties.

Quality Attribute	Abbreviation	Unit	Relevance
Biocompatibility	BC	/	Defined by the material
Biodegradability	BD	/	Co-dependent on porosity and dimensional accuracy. It is not possible to conduct measurements within the production process. Accordingly, not classified as an additional CQA.
Dimensional Accuracy	Ac	µm	Relevant for product quality, therefore classified as CQA.
Porosity	P	g/cm³	Co-dependent on dimensional accuracy but very relevant for product quality, therefore classified as CQA.
Layer Bonding	LB	%	Relevant for product quality, therefore classified as CQA.

The requirements for the design of the monitoring and quality control subsystems are based on the defined CPP and CQA. According to requirement P8 of the harmonized regulatory requirements from Chapter 2.3, all quality-critical process parameters must be monitored and controlled. Accordingly, the implementation of these controls is included as a function to be fulfilled in the morphological box for concept development.

3.1.3 Performance Criteria

The automation concept developed is intended to contribute to a fast, cost-efficient and quality-assured supply of individualized medical devices. Appropriate technical approaches, according to the basic requirements, are therefore ranked by the fulfilment of a number of criteria, which impact the production performance or are derived from regulatory guidelines (Schuh and Funk, 2019). These criteria are briefly explained and summarised in the Figure 29.

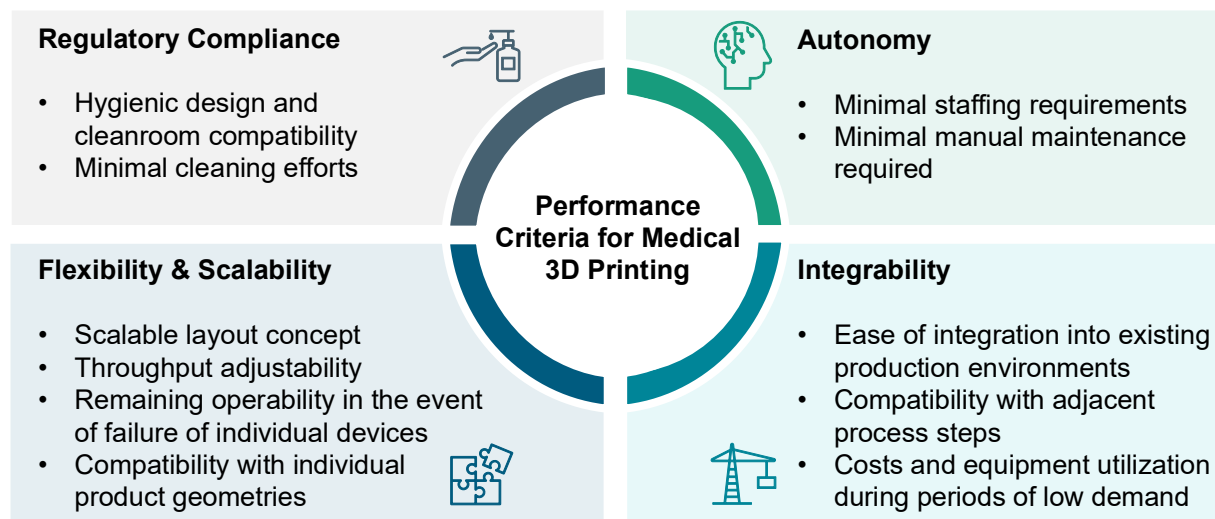


Figure 29: Criteria for evaluating the suitability and performance of individual solution approaches for system development

Regulatory Compliance for Medical Cleanroom Production

Medical devices that come into contact with human tissue are subject to high standards of hygiene and sterility, which is why they are manufactured under strict cleanroom conditions (Schuh and Funk, 2019). As part of the conceptual design, it must be ensured that automation approaches are suitable for use in cleanrooms and follow hygienic design principles. The most common practice to ensure this is to comply with GMP guidelines, whereby legally binding requirements specific for the country of approval must be met. These are specified, for example, by the EU in Europe and by the FDA in America. Along with this, the entire production must operate with a certified quality management system (Lhotská et al., 2019; Martinez-Marquez et al., 2019; Schuh and Funk, 2019), compare Chapter 2.3.

Autonomy During Production

A major advantage of automating the entire process chain is the decrease in personnel costs while maintaining product quality. To run the process safely and autonomously, elements for process monitoring and inline quality control are required. The accurate and instantaneous collection of process data allows for reactive and optimized control of process parameters, improving product quality and reducing process errors. Any developed automation concepts must be robust against possible malfunctions, e.g. faulty prints should not require manual intervention. The system must be able to detect malfunctions, react to them and, ideally, resume production independently.

Flexibility and Scalability for Adaptable Manufacturing

The production is targeted to produce individualized medical scaffolds in a dynamic and demand-oriented manner, which requires flexibility instead of linear process chains. A functional design should enable the system to serve different production quantities while using the same technical components. Existing systems should be expandable at a later date with little effort. Particularly expensive devices like extruders should be optimally utilized to avoid unproductive downtime. The customization of individual medical products to patient-specific features requires batch-size-one production while maintaining high throughput. The solution concepts must therefore be able to adapt to different product geometries automatically. A key feature of flexible production is the ability to maintain operability when individual devices break down.

Integrability for the 3D Printing Process

The selection of solution concepts must consider the extent to which the identified approaches are compatible with existing solutions and can be integrated into process workflows. Suitable solution concepts are characterized by a system design, which allows an integration of different or additional devices for example a specific quality control. For the interfaces between the defined subfunctions, it is crucial that they are compatible between adjacent process steps. This applies to both hardware and software interfaces. Individual modules of the 3D printing system should not interrupt or otherwise influence the production process. The assessment of integrability includes an economic comparison between the approaches. If the value of the approaches is the same, the most cost-effective solution is chosen. The four defined performance criteria are used to evaluate the solution approaches collected in the following morphological box.

3.2 Morphological Box for Collecting Automation Approaches

The overall methodology for the identification, evaluation and selection of automation solutions is visualized in Figure 30. The focus is set on the morphological box method for the collection and comparison of different technical approaches (Zwicky, 1967). The left column of the morphological box is formed by the function tree derived from the production process itself, described with Figure 27. Based on the functions to be fulfilled, as shown in the function tree in Figure 28, technical solution approaches are exploratively searched for in the literature. For the explorative literature research for each individual function, search criteria are chosen and both scientific and, in particular, industrial publications are considered in order to also identify established solutions. During the first review, the technologies are evaluated in terms of their ability to fulfil the function. During the second review, a decision is made on whether an implementation would be realistic considering the defined use case. This variety of possible solutions fills the matrix of the morphological box, as shown in Figure 31.

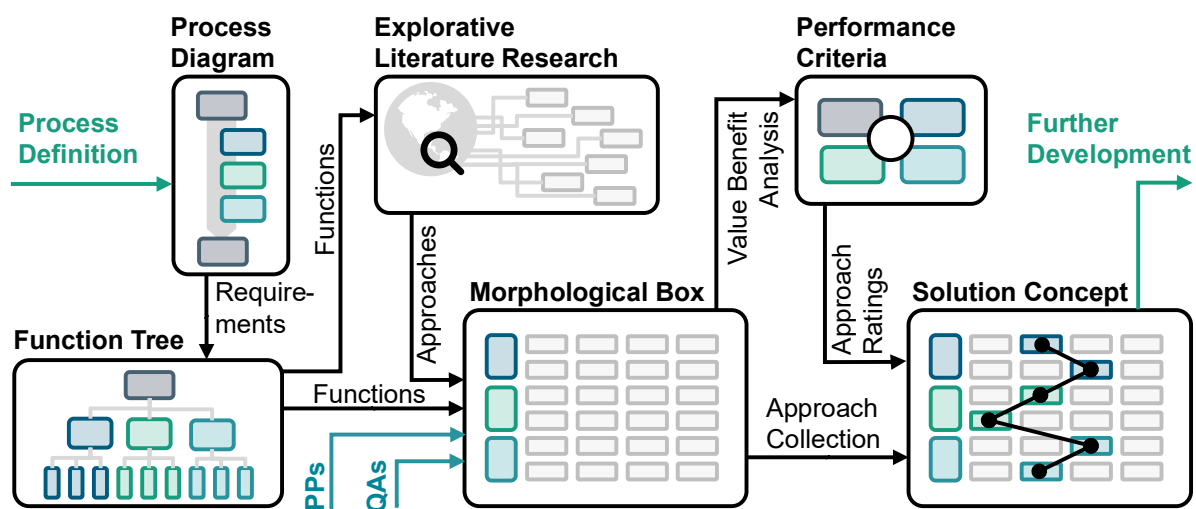


Figure 30: Schematic visualization of the used morphological box method with inputs and outputs (Janning et al., 2025)

For the exploratory literature research to fill the morphological box with technical approaches to holistically automate the EAM process, three measures are pursued. Firstly, industry magazines covering the topics of automation, additive manufacturing, metrology or production logistics are screened for articles addressing the individual functions. Secondly, for more research-related questions, Google Scholar is used to search for scientific publications that offer potential technical solutions. Thirdly, the systematic creativity method SCAMPER is used to find ideas for problems for which the literature offers no directly suitable approaches. SCAMPER stands for Substitute, Combine, Adapt, Modify, Purpose, Eliminate, Rearrange. The technique is based on the assumption that innovations can arise from the modification or combination of existing ideas. In this case, the technique is used to evolve technical approaches that seem unsuitable on their own by asking seven SCAMPER questions. This then leads to new ideas that ultimately can potentially fulfill all requirements (Merten, 2020). One example of this, with specific regard to this application, concerns the axis kinematics of the 3D printer. The requirements dictate that the kinematics should be as abrasion-free as possible

for operation in a cleanroom and at the same time should be as flexible and scalable as possible in order to achieve a high extruder utilization rate. Published approaches from research and industry do not offer a completely satisfactory solution. Asking the C-question, whether multiple functions could be combined and solved together, led to the idea of using a magnetic planar drive system, which is usually used for production intralogistics, for the horizontal printer kinematics as well (compare Chapter 2.2.1). Ultimately, the following morphological box results from the three approach-finding measures for all functions.

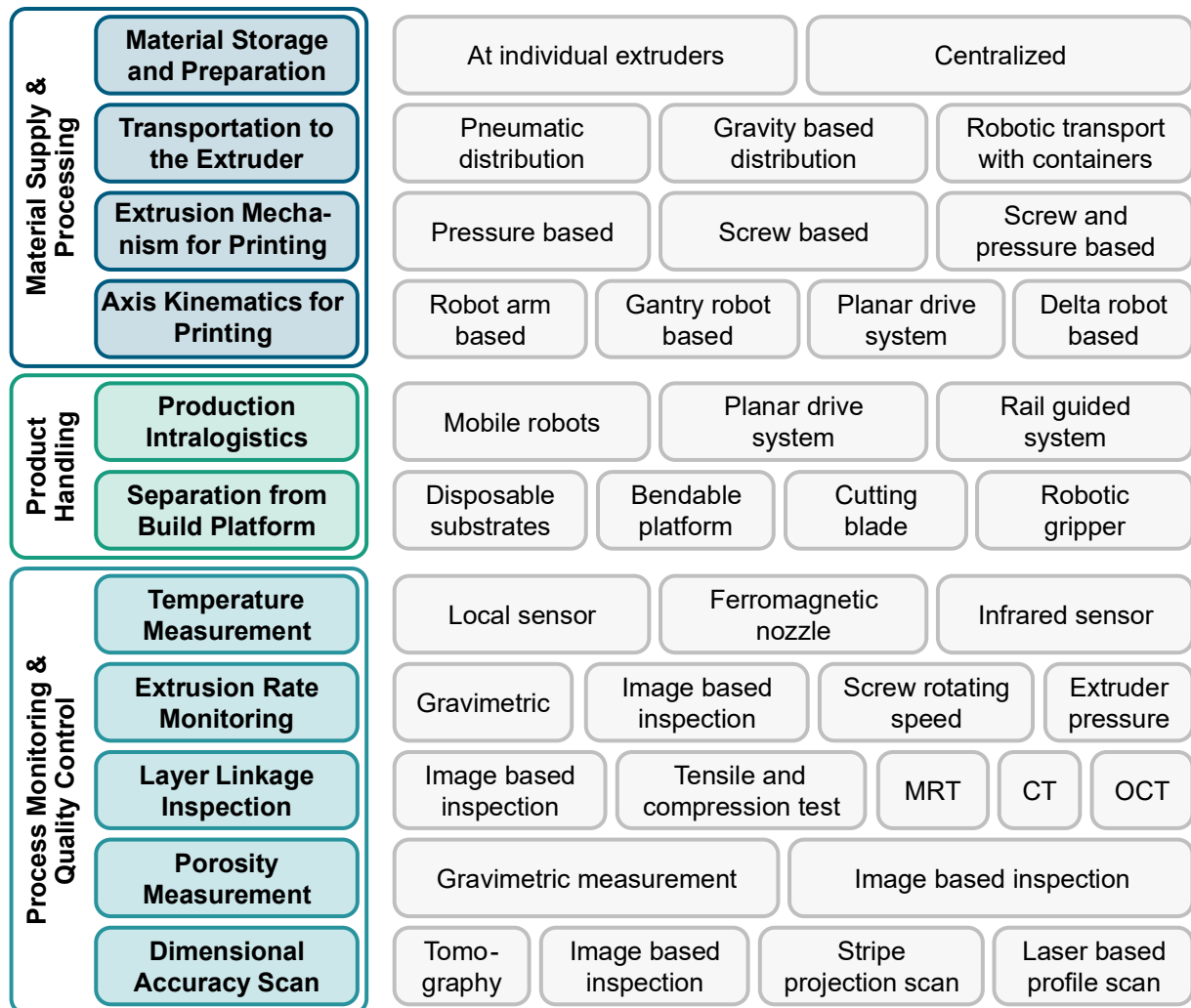


Figure 31: Morphological box with an unsorted collection of possible solution concepts for the individual attributes

3.3 Value Benefit Analysis for Selecting Automation Solutions

In the last review of the approaches, a value benefit analysis is carried out with the selected technologies from the morphological box, whereby a qualitative assessment is made of the extent to which the individual solutions meet the performance criteria regarding first regulatory compliance, second integrability, third autonomy and fourth flexibility and scalability, as shown in Figure 29. The evaluations are documented using a Harvey Ball score (Kellen, 2003), as can be seen in Figure 32.

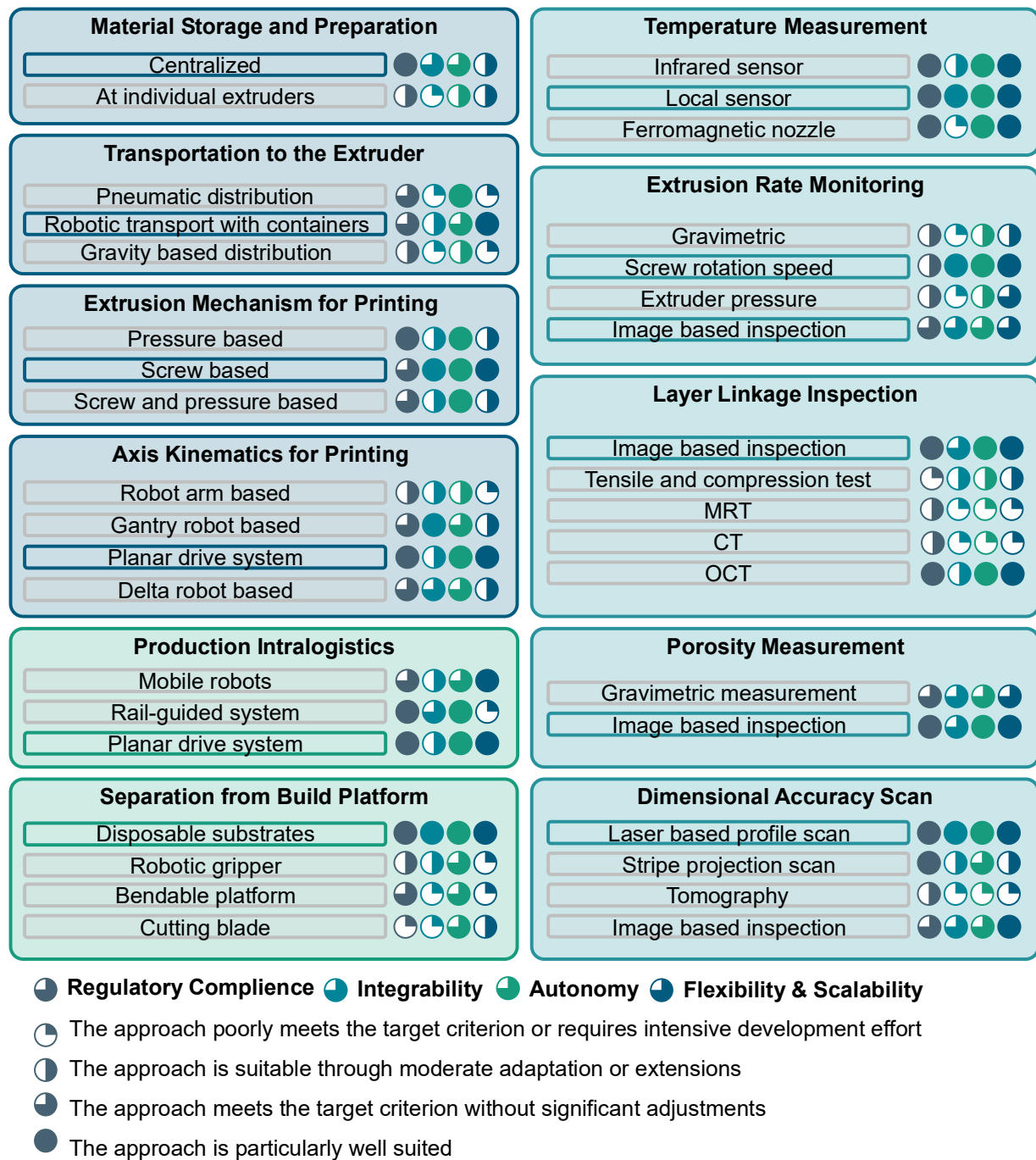


Figure 32: Harvey Ball ratings of the individual solutions collected in the morphological box

This scoring includes considering all the approaches in the morphological box holistically and in terms of their combinability with each other. The weighting of the individual performance criteria is assumed to be identical, so that a summation of the individual Harvey Ball Scores for each approach results in a total rating. These ratings of each approach are used to highlight the best-rated combined approach in the morphological box, which allows to derive the final solution concept for the scalable production infrastructure.

More detailed explanations for the best rated approaches listed in the morphological box are explained within the following chapter regarding the derivation of the final automation concept.

3.4 Derivation of the Final Automation Concept

The selection of automation approaches for the solution concept is based on the results of the value-benefit analysis and is displayed in the final morphological box in Figure 33. In the following, a statement is made for each decision in favor of a selected solution approach.

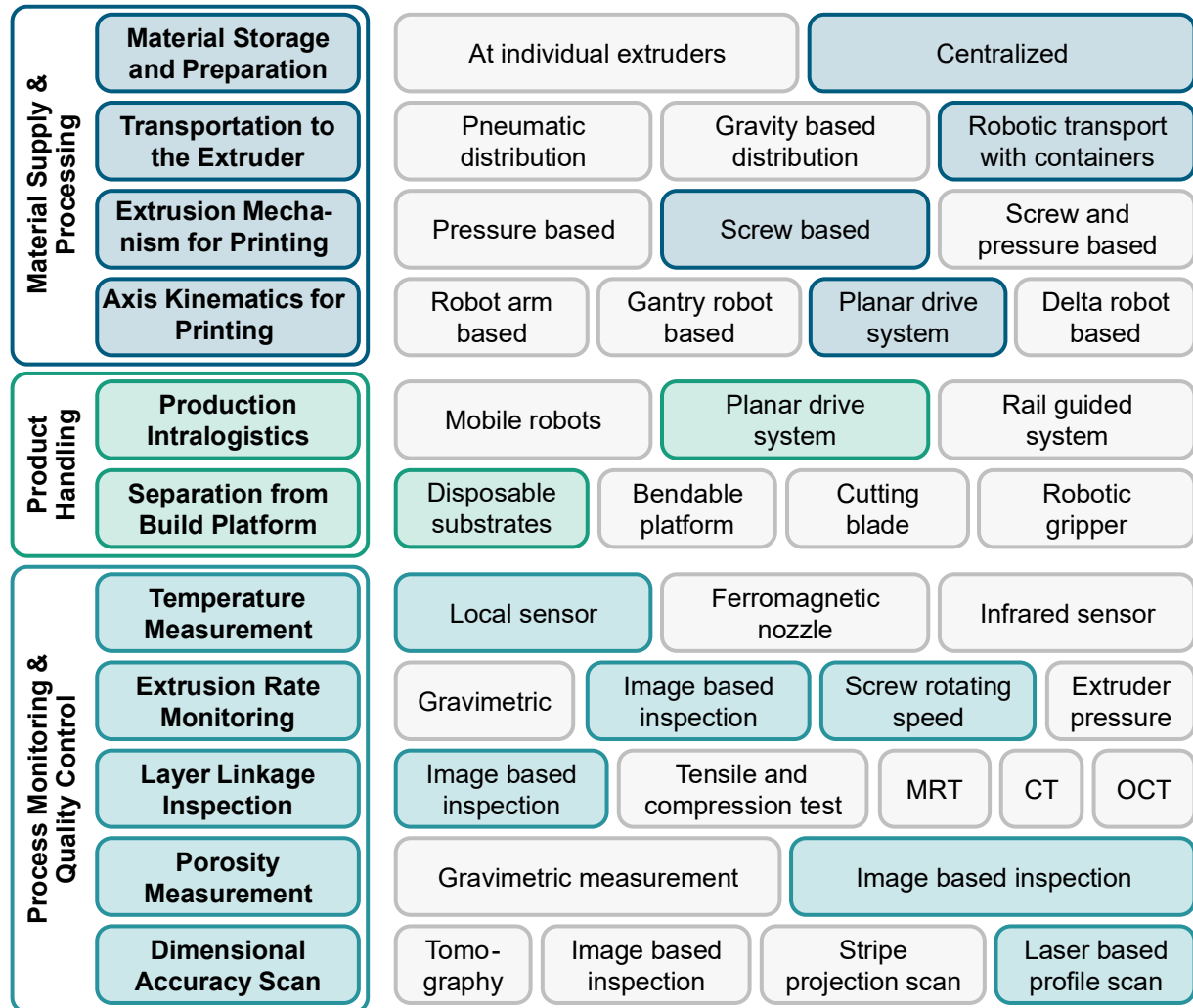


Figure 33: Morphological box with identified solution approaches evaluated according to the performance requirements (Janning et al., 2025)

3.4.1 Material Supply and Processing

Centralized Material Storage and Preparation

This approach involves storing the granules in a temperature-controlled central dispensing tank. An integrated dispensing system enables precise and automatic filling of transport containers in a cleanroom-compatible manner. For incoming material, the granules must be refilled manually at appropriate intervals. Commercially available solutions for different scales exist, which allow the storage of several 100 kg of granulate, which would correspond to several thousand scaffolds. Such systems are well established in the plastics processing, pharma and food industries (Volkmann GmbH, 2024), which is why no further development work would be required for implementation. The degree of innovation is correspondingly low. It should be noted that a low humidity level must be guaranteed when processing PCL. The integration of a drying system is therefore recommended for maintaining predictable processability. The process parameters that are derived by this approach are the average humidity, the average storage temperature and the storage time of the granules between opening the primary packaging and the beginning of processing. Individual storage of the granulate at the extruders would have the disadvantage of increased integration efforts and individual monitoring of the storing conditions being required.

Robotic Transport of Granulate Container to Extruder

Due to the centralized supply of the granulate, an automated transport system between the dosing station and the extruder must be designed. It must be possible to adapt the system depending on the number and positioning of the extruders in operation. Flexibility is therefore necessary. A solution was chosen that involves transport containers being filled with granulate at the central dosing station and then being transported to the extruders by mobile robots. Due to the only temporary transportation in the transport containers, additional tempering of these is not considered. When using containers, it is only necessary to ensure that the surfaces that come into contact with the granules meet hygiene standards. It is not necessary to seal the containers during transportation due to the cleanroom environment, as long as the container opening is not moved below possible sources of particle abrasion. Suitable vessels of this kind are commercially available. Compatibility with the gripper of the mobile robots must be ensured.

Autonomous mobile robots for intralogistics tasks in production have already been established for a number of applications (Unger et al., 2018), as well as for more complex material handling in laboratory applications (Kleine-Wechelmann et al., 2022). Although the implementation effort is increased due to the teaching of the movements, such as filling and emptying the granulate container, and due to the training of the recognition of the dosing station and the extruder chute, this approach is particularly useful in terms of scalability and flexibility. The development effort and the degree of innovation are rated as moderate.

Screw-based Extrusion for 3D Printing

For the extrusion of PCL, the melted granulate is pressed through the nozzle either by an extruder screw, by applying pneumatic pressure or by a combination of both methods. Specifically for PCL, an extruder screw is sufficient and more cost-effective than a pneumatic system. The considered process parameters of extrusion rate and extrusion temperature can be easily set for a screw-based system.

Planar Drive powered Horizontal Axis for 3D Printing

A magnetic planar drive is chosen as an unconventional approach for implementing the kinematics of the 3D printing process. In this approach, so-called movers, consisting of permanent magnet arrays, are held in magnetic levitation and can be positioned in the plane with a tolerance of 50 μm . The mover therefore acts as the build platform for 3D printing but is physically independent. In a previous publication, the industrial use of magnetic planar drives in production was discussed in detail (Janning et al., 2022). The use of a magnetic planar drive for 3D printing was first presented in 2022 within the patent WO2023094674A1. The concept was investigated and validated within the publicly funded German Bundesministerium für Bildung und Forschung (BMBF) research project “BellaFactum” (Funding ID: 13GW0497B). The planar drive is used for the X and Y axis for 3D printing, while the extruder is mounted on a linear electric Z-axis. The advantages of the concept are:

- Frictionless movement and thus the minimization of particle abrasion, which increases the cleanroom suitability.
- Direct connection to the production intralogistics and thus the possibility to decouple the print bed from the extruder and move to another station, for example for quality control.
- Minimization of downtime, as multiple movers can serve one extruder. For example, while a printed layer on one mover is cooling, another layer can be printed on a second mover.
- Scalability, as the planar drive can modularly be enlarged in its surface area and throughput can be increased by adding further extruders and movers.

Due to the novelty of the approach, a proof of principle is provided as part of the development of the holistic solution concept, which is why the degree of innovation for this approach is classified as high. In Chapter 5.1.1 the conducted experiments on planar drive-powered 3D printing are presented in detail. The approach adds the mover levitation height as a potential quality influencing process parameter, which is considered in the process influence analysis in Chapter 3.5.

3.4.2 Product Handling and Production Intralogistics

Planar Drive-based Production Intralogistics

The use of a planar drive system for the horizontal kinematics of the 3D printer enables direct connection to the production intralogistics at the same time. Since the stator area can be extended as required, further processing or quality control stations can simply be docked onto the system and all transport steps can be accomplished by the planar drive. Only for special intralogistics steps such as storing finished products on shelves, multi-axis robots are required.

The planar drive with multiple movers can be understood as a dynamically interconnected multi-agent transport system. Even if linear process chains can be mapped with the system, it is useful to evaluate free-chained adaptive approaches that allow a mover to target different destinations depending on for example the result of a quality control or the availability of a station. Additionally, it is necessary for the logistics to react adaptively due to the personalized products and the resulting impossible preliminary scheduling of discrete process steps. The implementation of such multi-agent path finding (MAPF) algorithms is currently the subject of research (Stern, 2019), but they have not yet been fully established in the industry, which is why the degree of innovation is considered to be high. Process parameters that are relevant for this internal logistics have no interface with the product itself, so they are not considered further, except for later throughput optimizations.

Disposable Substrates for Build Platform Separation

The individual movers of the planar drive act as the build platforms, with an exchangeable substrate plate mounted on top. On the upper surface of these substrates, the PCL is extruded on. The substrate plates are designed as disposables and, together with the finished scaffold, are considered as the final product. The separation of the scaffold and the substrate plate can be done outside of the production environment, manually at the point-of-care. Mounting on the movers can be done using suitable brackets and a robotic gripper. Suitable substrate plates for printing PCL are commercially available and do not require further engineering. The surface quality of the substrate plates is highly important for the success of the 3D print because if the adhesive properties are insufficient, warping effects (Ramian et al., 2021) can occur or the extruded layer can peel itself off the substrate during printing. Too adhesive substrate properties prevent the scaffold from being removed non-destructively. The compatibility of the substrate material and the material to be printed must therefore be validated in each case. If this is the case, there are no additional influential process parameters for the production.

3.4.3 Process Monitoring and Quality Control

Local Sensors for Nozzle Temperature Monitoring

A local thermocouple is the most established and cost-effective solution for monitoring the nozzle and extrudate temperature, which is why this approach is chosen.

Extrusion Rate Monitoring via Screw Rotation and Image Inspection

The extrusion rate can be monitored in a screw-based extruder via the screw rotational speed, given that the system is appropriately calibrated. Since air inclusions can potentially occur due to inhomogeneous granule size, and thus cause temporary extrusion interruptions, additional monitoring is required. This is done by capturing high-resolution images of the individual printed layers. Automated evaluation algorithms can be used to determine whether over- or under-extrusion has occurred. The magnetic planar drive as an intralogistics transport system allows the mover to move to a camera station to inspect a printed layer and then move back to continue the print at the extruder or to a disposal station to remove the substrate with the defect scaffold.

Image-based Layer Linkage Inspection

The cross-linking of the filaments of the individual layers can be evaluated using the same images as for extrusion monitoring. This test assumes that if the extrusion was dimensionally accurate without over- or under-extrusion, then the linking is also accurate. A 100 % validation can only be carried out using tomographic methods. Magnetic Resonance Tomography (MRT) or Computed Tomography (CT) is not economically viable for this application. Optical Coherence Tomography (OCT) is a possible alternative. However, it still requires additional integrative efforts and object dependent calibrations, compared to conventional image recordings.

Image-based Porosity Measurement

The porosity of the scaffolds correlates with the density of the scaffold and is defined by the distances between the individual filaments of a layer. These filament distances are also measured using the layer geometries determined by image evaluation.

Laser-based Dimensional Accuracy Scan

The final quality control of the scaffolds involves measuring the external dimensions. For this purpose, laser distance measurement is used to create point clouds of the external dimensions of the finished scaffold. By comparing the measured values with the planned geometries from the computer-aided design (CAD) model of the scaffold, a decision is automatically made whether or not the quality parameter for dimensional accuracy is within the tolerance range.

3.4.4 End-to-End Automation Concept for Personalized Medical Scaffolds

The combination of the individual technical approaches, described in the previous subchapters, results in a holistic concept for a production infrastructure for the use case of personalized medical PCL scaffolds. The hardware concept is shown schematically in Figure 34 but without the surrounding clean room.

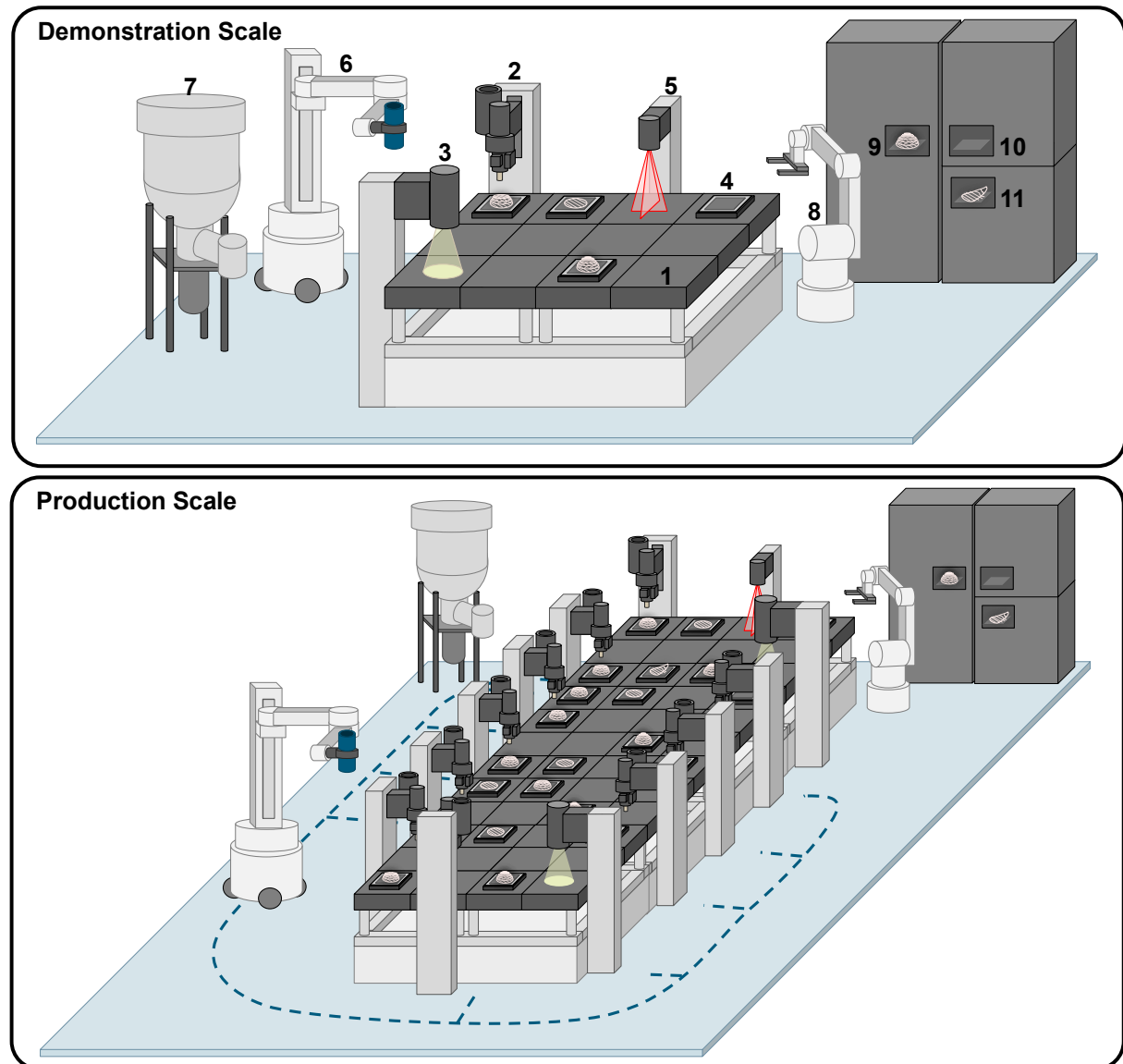


Figure 34: Production infrastructure in demonstration scale (above) and in production scale (below) for increased throughputs. 1: Planar drive system, 2: Granulate extruder including Z-axis, 3: Microscopic camera for image-based quality control, 4: Mover with mounted substrate plate, 5: Laser depth scanner for quality control, 6: Mobile robot for granulate container transport, 7: Granulate storage and dosing machine, 8: Robotic arm for product handling tasks between mover and storage, 9: Storage for finished implants, 10: Storage for ready to use substrates, 11: Storage for failed prints. (Janning et al., 2025)

The process flow is as follows: The individual movers of the magnetic planar drive (1) are loaded by the robot (8) from the substrate storage with a sterile disposable substrate. The movers, ready for printing (4), then move to the extruder (2), which is mounted on a vertical

linear axis. The linear axis and the two horizontal axes of the planar drive then execute the printing paths of the individual layers during synchronous extrusion of the material. Depending on the configured cool-down time, a pause is scheduled between each layer, during which the mover moves to its home position and waits. Concerning the associated logistical processes, the extruder is initially filled with granulate by a mobile robot (6). The granulate is provided in a central reservoir including a dosing system (7). The reservoir is cooled so that the prescribed storage conditions for the granulate are maintained. The dosing unit gravimetrically meters a defined mass of granulate into the mobile robot's custom transport container using a screw drive. The robot can then transport the granulate to the corresponding extruder and dock it onto the opened hopper. An ultrasonic sensor detects when the available material in the extruder falls below a certain threshold and triggers a new granulate filling process.

Quality control steps can be added between the fabrication of individual print layers or at the end of the printing process. The concept shown here involves moving the movers to a camera station (3) after printing a defined number of layers, where high-resolution images of the last printed layer are taken using a reflected-light camera. These images are then used for multiple purposes: Firstly, to check the position and thickness of the printed filament lines to detect whether over- or under-extrusion has occurred. Secondly, the layer linkage is checked. Based on the shading at the intersections between horizontally and vertically placed filaments, it can be interpreted whether the filaments are fused or floating on top of each other and no layer linkage is achieved. If a defined tolerance threshold of unlinked intersections is exceeded, the print is declared defective. Thirdly, porosity is determined by measuring the distances between the filament lines and therefore interpreting the material to volume ratio.

For the final inspection, the finished scaffolds are moved to the laser depth scanner (5), where a point cloud of the scaffold is recorded in order to interpret the outer dimensions of the scaffold. This allows the detection of deformations such as warping, which can occur due to thermal stresses in the material during and after the printing process. The finished and inspected scaffolds are then returned to the separator station, where the robot arm removes the substrate plate including the scaffold from the mover and transfers it to an automated storage system (9). If a printing process has to be aborted, the substrate with the defective scaffold is transferred to a different storage location (11). The mover is then loaded with a new scaffold and the same printing process is repeated. If waiting queues occur at extruders or quality control stations, the mover with the previously failed print job is given priority. The automated process ends with the personnel filling the storage tanks with new substrate plates and removing the finished or damaged scaffolds from the storage. In addition, the central granulate reservoir is refilled manually.

The production infrastructure can be scaled in terms of throughput, which is defined as scaffolds produced per unit of time. To realize this, the surface area of the magnetic planar drive is expanded by attaching additional tiles and additional extruders, including their linear axis (compare Figure 34, below).

Concerning the software infrastructure of the concept, Figure 35 shows the connections between the individual control components and control software for the conceptualized

production infrastructure. Most of the devices, such as the planar drive, linear drives, extruder components, the dosing unit motors and the automated storage systems, are directly connected to the Programmable Logic Controller (PLC) in the electric cabinet. Devices such as mobile and stationary robots have proprietary controllers for operation. Although these controllers can be physically integrated into the electric cabinet, the individual motors are not controlled directly via the PLC.

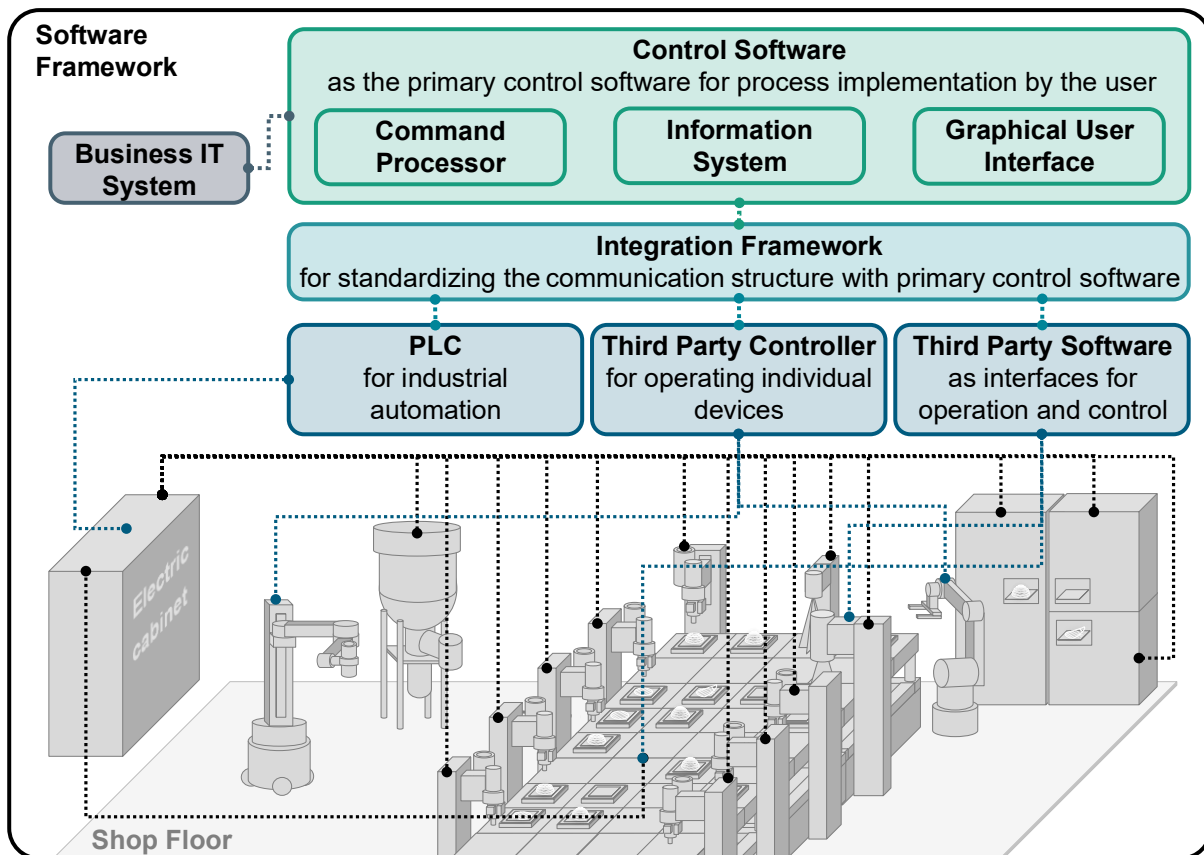


Figure 35: Conceptualized software framework for the production infrastructure with its main components (Janning et al., 2025)

Other devices, such as cameras, are connected directly to a computer running a Windows® operating system and are operated using proprietary software. Other programs, such as algorithms for image evaluation, run locally on the computer via third-party software environments like Python® and can communicate with the PLC software environment. This communication between the PLC and third-party software is essential for implementing complex path-planning algorithms for the simultaneous coordination of all movers to avoid collisions and allow parallel adaptive processes. Simpler MAPF solver can also be implemented directly via the PLC. The PLC, other controllers and software communicate with an integration framework that provides an interface driver for each individual hardware device and enables connection to a higher-level control software. The COPE (Control Operate Plan Execute) control software is used as the overarching communication level, allowing a FDA CFR Part 11 compliant orchestration of the production (Hort et al., 2023; Jung et al., 2018). Table 31 in Annex A.8 summarizes all the components that were considered for the finalization of the production concept and were partially implemented for the construction a demonstrator.

3.5 Process Influence Analysis

Based on the newly developed concept for fully automated EAM, a process influence analysis is carried out. This is used, on the one hand, to examine whether the newly designed process steps have resulted in new process parameters that have not already been considered by the literature review. On the other hand, it is systematically checked whether these parameters interact with each other. Finally, the list of process parameters classified as critical in Chapter 3.1.2 is revised and taken into account for further development of the production system. Figure 36 illustrates the process influence analysis method in the context of the overall methodology. In the next chapters, this will be followed by the modularization of the system concept and the development of a demonstration system.

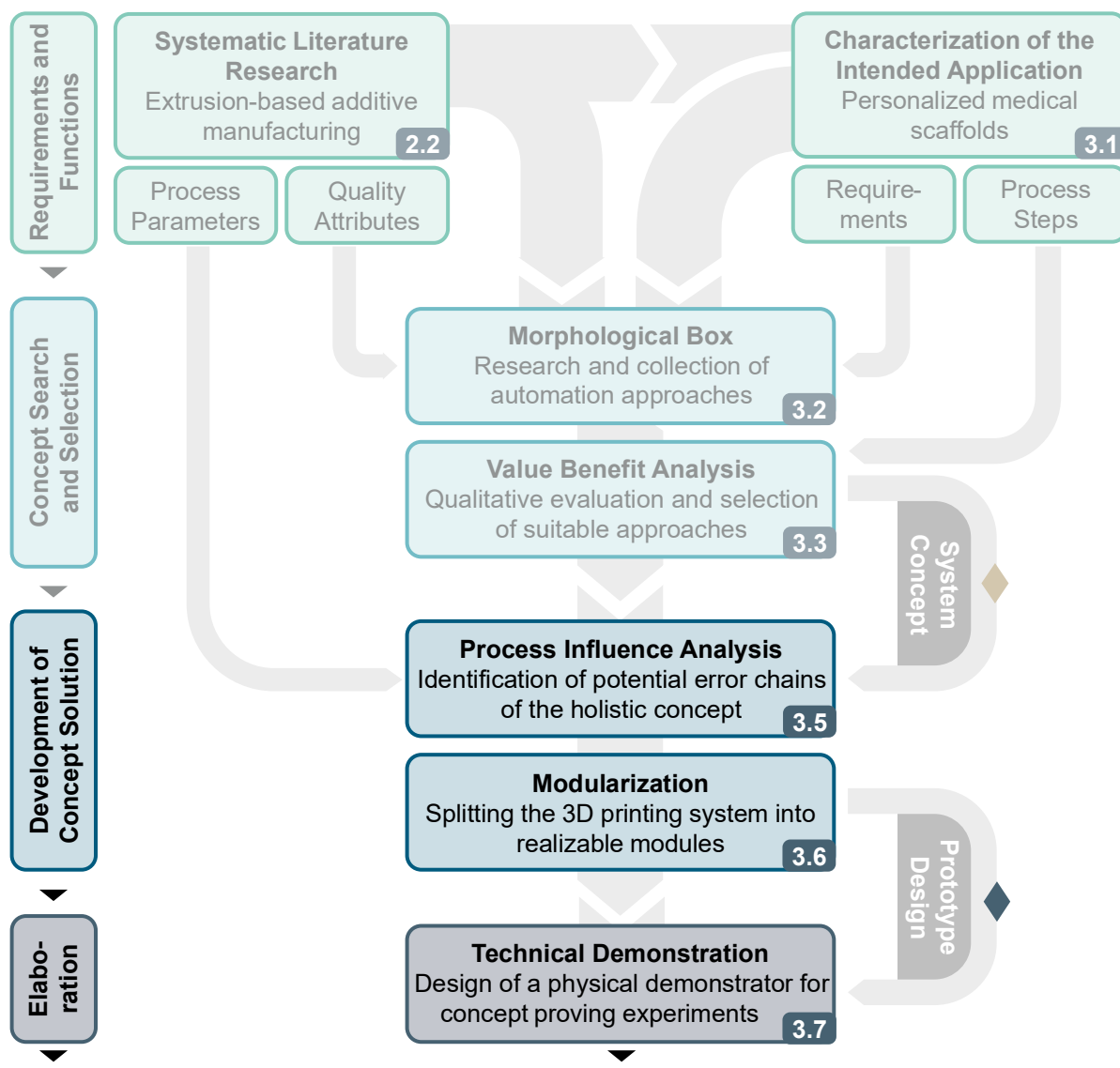


Figure 36: Extract from the overall thesis methodology presented in Figure 23 and Figure 24

Figure 37 illustrates the process influence analysis with, on the left-hand side, the solution concepts for the individual functions resulting from the morphological box and the utility value analysis. The right-hand side shows, on the one hand, the process parameters that have

already been identified by the literature review and, on the other hand, further process parameters that result from the new concepts. The arrow links indicate which processes influences which parameters. Since the process parameters can also interact with each other, the influences are shown by the arrow connections on the outer right side.

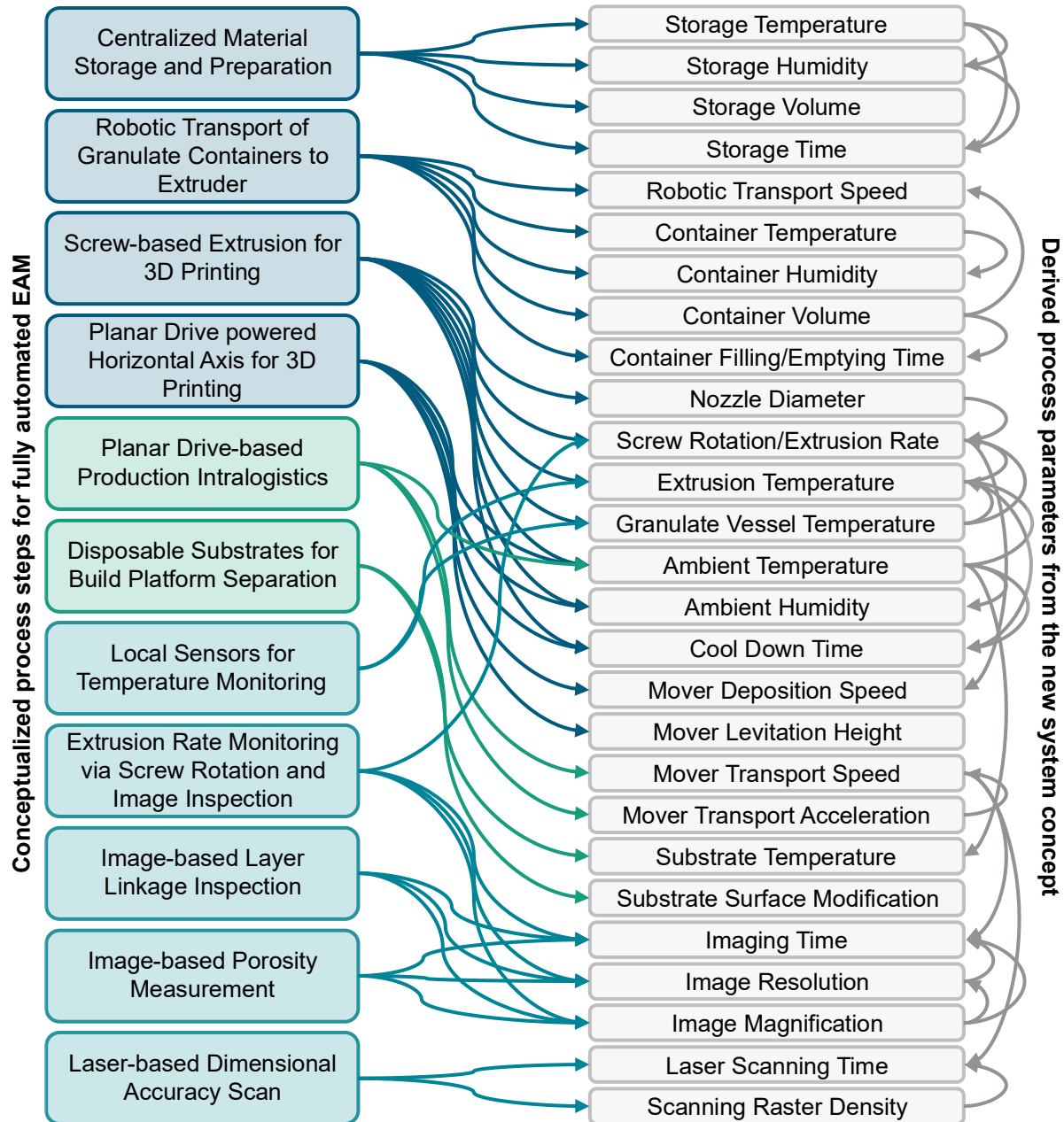


Figure 37: Process influence analysis for fully automated EAM

In the next step, the identified process parameters were examined individually in terms of their possible influence on the quality attributes of personalized medical PCL scaffolds, compare Chapter 3.1.2. The most relevant process parameters of the conceptualized production system and their potential influence on the quality attribute classes are summarized in Table 8 and explained below.

The nozzle diameter has an influence on the geometrical properties of the product, as it allows for narrower or wider filament formation. The probability of over- or under-extrusion is

influenced by the interaction of nozzle diameter and extrusion rate, which also affects the mechanical stability of the product. The process parameter deposition speed, which is realized by the movement of the movers, can influence the printing precision under certain circumstances. Due to the inertia of the movers at higher speeds, there is an increased risk of oscillation, which can lead to local deviations from the reference trajectory of the movers. The systems maximum permissible speeds and accelerations must be validated depending on each use-case.

Table 8: Summary of process parameters of the production concept

Process parameter	Symbol	Unit	Affected quality attribute class
Nozzle Diameter	d_{Nozzle}	mm	Geometrical
Extrusion Rate	V'_{Ex}	ml/s	Geometrical, Mechanical
Mover Deposition Speed	v_{Mover}	m/s	Geometrical
Mover Levitation Height	h_{Mover}	mm	Geometrical, Mechanical
Extrusion Temperature	T_{Nozzle}	°C	Geometrical, Mechanical, Biomedical
Ambient Temperature	$T_{Ambient}$	°C	Mechanical, Biomedical
Ambient Humidity	$H_{Ambient}$	%	Mechanical, Biomedical
Cool Down Time	t_{Cool}	s	Geometrical, Mechanical

The mover levitation height is another process parameter that is added by the new concept. While a mover is moving in a horizontal plane, in the vertical direction fluctuations in the levitation height can occur, described as wobbling. This wobbling can be influenced by the set levitation height itself, the movement performed, the load to be carried and the position on the planar drive. More significant wobbling, by $\pm 0,5$ mm or more, can cause the extrusion filament to break, ultimately leading to both geometric and mechanical influences. The extrusion temperature or the nozzle temperature, is a critical parameter as it has a direct influence on the material viscosity and the curing during extrusion. This affects not only the geometric properties but also the mechanical properties since the cross-linking between the layers is temperature and viscosity dependent. The general ambient temperature and humidity in which the products are located have an influence on the mechanical properties and biodegradability since PCL is hydrophobic and would absorb water in warm, humid environments, which would lead to premature uncontrolled decomposition of the material. The cooling time between layers specified by the user has an influence on the thermal stresses that build up in the material. If all layers are printed directly one after the other, the lower part of the product will be significantly warmer than the upper part for a longer period of time. This results in uneven cooling and thus in some areas to an expansion, which can lead to the warping effect and thus to the failure of the print.

The process influence analysis only considers these influence relationships in a purely qualitative way and their proportionality is not validated. Nevertheless, the analysis provides a holistic view that supports the consideration of all potential influences and their adoption in further technical development.

3.6 Modularization of the Production System

The development methodology, shown in Figure 36, states that after the overall concept has been evaluated, it is divided into modules for further technical development. These development modules are shown in Figure 38. The modules outlined in blue are integration tasks. The devices used are established products whose installation does not present a development hurdle and only shows a low degree of innovation. Accordingly, the specific technical implementation is not examined in detail in the context of the concept development of the production infrastructure. The modules with teal outlines indicate a certain level of complexity and implementation effort. This involves quality control mechanisms, including image-based evaluation. Training data and extensive testing are necessary to establish reliable feature recognition. Extensive preliminary work has already been done in the area of error detection for 3D printing scaffolds (Bill Tseng et al., 2014; Charia et al., 2025; Irsen et al., 2006; Li et al., 2022; Montalti et al., 2024; Sani et al., 2024). Accordingly, the degree of innovation is considered moderate, which is why a more in-depth elaboration of a solution implementation for this specific use case is not considered within this work. Instead, Chapter 3.6.2 presents the integration concept and its functionality in more detail. The modules framed in green are the key aspect of the production concept but also represent the greatest technical challenges and show a high degree of innovation. Thus, the elaboration of planar drive-based 3D printing, production intralogistics and enabling MAPF is explained in more detail in the following.

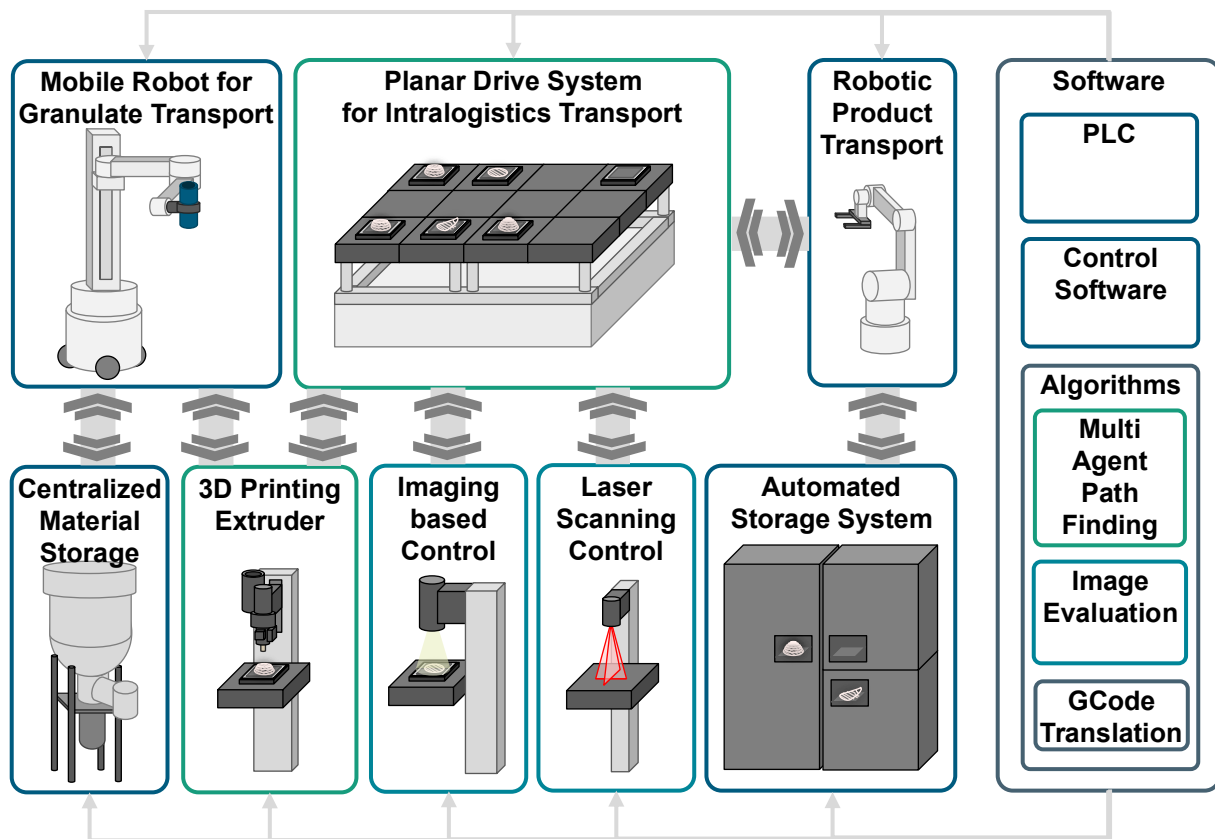


Figure 38: Development modules of the production infrastructure and their interconnections

3.6.1 Magnetic Planar Drive-based Extrusion Additive Manufacturing

The use of a magnetic planar drive as a horizontal axis plane for 3D printing is a new approach, which is why the term Planar Drive-based EAM (PEAM) is introduced at this point. The advantages of the concept were presented in Chapter 3.4.1. Figure 39 visualizes the basic design of the concept with its individual components and shows an initial laboratory set-up. As part of the development of a demonstrator, a Beckhoff XPlanar system was used, which is operated with the Beckhoff PLC Environment TwinCAT (Beckhoff Automation GmbH). A mover can be implemented as a numeric control (NC) axis analogous to conventional linear axes, whereby a mover can map two axes. Open-source TwinCAT modules such as a G-Code interpreter can be linked to the mover accordingly to be able to read the G-Code files, established for 3D printing. A conventional linear axis including a stepper motor is installed as the third axis for vertical movement, on which the extruder is mounted perpendicular to the planar drive surface. The axes are synchronized accordingly to be able to perform all necessary 3D movements.

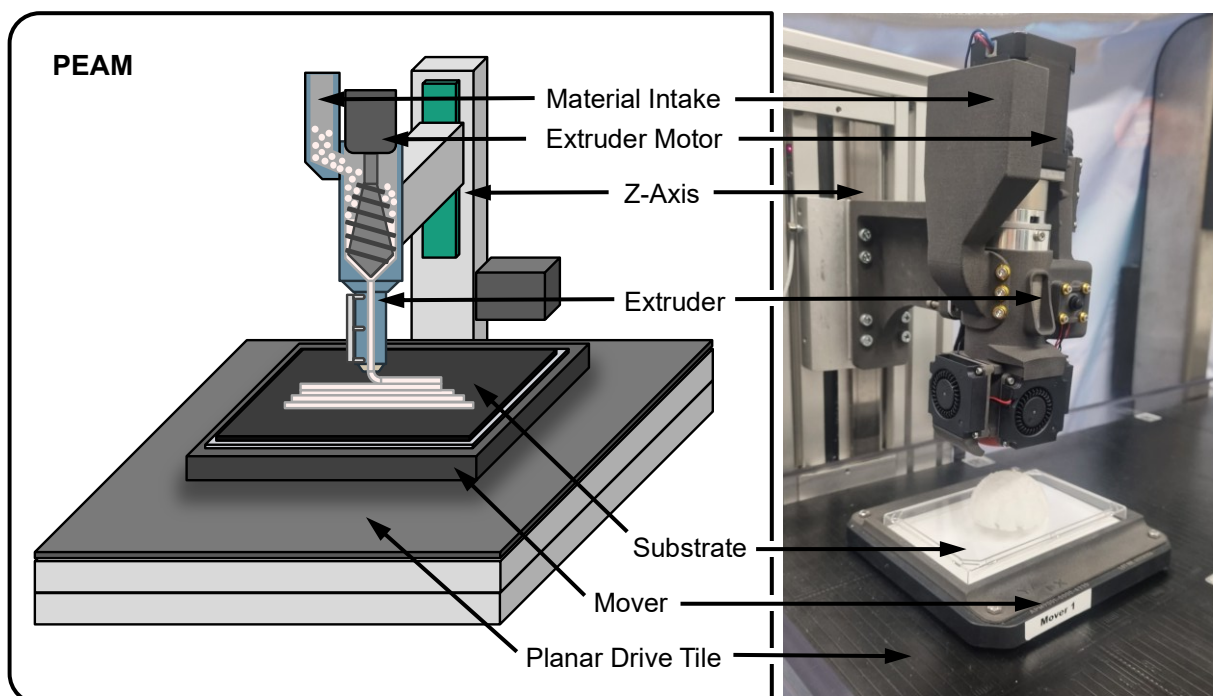


Figure 39: Planar drive-based EAM concept with schematic drawing (left) and demonstration set-up (right)

For the leveling of the Z-axis in relation to the mover surface, more specifically the substrate surface, there are different approaches. The manual bed leveling approach is to move the Z-axis manually until the extruder nozzle approaches the mover, levitating at its operational height. A leveling film can then be placed between the substrate and the nozzle so that a specific distance is set when the nozzle hits the film.

The properties of the planar drive also allow a new approach for automated print bed leveling to be investigated, which is based on force measurement by means of magnetic field changes. The movers are held in a levitation state by generating a magnetic force that counteracts the mover's weight force. This magnetic force is generated by the permanent magnetic properties of the movers and the corresponding counter-polar charging of the coils of the planar drive,

compare Chapter 2.2.1. Since the movement of a mover can simultaneously induce a current in the coils that can be measured, the system can determine the position of the movers and cyclically readjust them with the corresponding precision. If the levitating height of the mover changes, the magnetic field density in which the circuit paths of the coils are positioned also changes. Thus, the system can also control the position in the Z-direction. Since the weight of the mover changes depending on its load, based on the current required to generate the levitation height, the system can calculate the mass of the mover and thereby also the mover load. This effect can also be used to detect other forces acting on the mover. By slowly moving the extruder nozzles against the substrate of the levitating mover, the system detects this external force and can thus identify exactly at which height the nozzles hit the print bed. The nozzle height can then be automatically leveled by a corresponding offset. However, it should be noted that this nozzle touchdown must be carried out with a heated nozzle, otherwise cold hardened polymer residue on the nozzle tip would falsify the positioning.

A fixed levitation height of 4 m was set. Qualitative observations have shown that the so-called wobbling effect occurs at a lower levitation height of about 2 m. The wobbling effect describes irregular fluctuations in the levitation height while the mover is moving in a horizontal plane. A higher levitation height can apparently be kept more constant during movement.

3.6.2 Inline Integration of Quality Control Stations

The elaboration of the module for inline quality control focuses on its infrastructural integration and functionality and not on data acquisition and evaluation for quality assurance purposes. The developed concept intends for the scaffolds to remain on the movers during fabrication, and for the movers to decouple from the extruder together with the semi-finished scaffolds so that they can be inspected using different QC measures. The path planning strategy enabling this, is considered in the following chapter. Depending on how the system boundaries are set around the process, the decoupling can be considered as either online or in-line process control. In-line process control involves data collection directly in the process. Online process control involves data collection from the process via a bypass. On the one hand, the decoupling of the mover and transport to a separate QC station can be interpreted as a bypass. On the other hand, the pause between layers is necessary for cooling and thus part of the process, which is why the designed QC integration can be considered inline-capable.

Exemplarily, as part of the concept development, an imaging station was implemented to capture images of the scaffolds. A microscopic digital camera (Dino-Lite AF4915ZTL) was installed and can image the scaffolds within the given working distance, either in their entirety or at specific points with 10 x optical magnification. The camera is mounted on a linear axis for vertical positioning to allow focusing the Z-plane depending on the scaffold layer to be viewed. The Z-axis is controlled analog to the extruder via the PLC, while the cameras are operated via third-party software. The higher-level control software COPE enables the cross-device automation of processes. Figure 37 shows the laboratory setup of the imaging station (A) and a semi-finished test scaffold that was printed on an aluminum substrate, being imaged after its fifth layer.

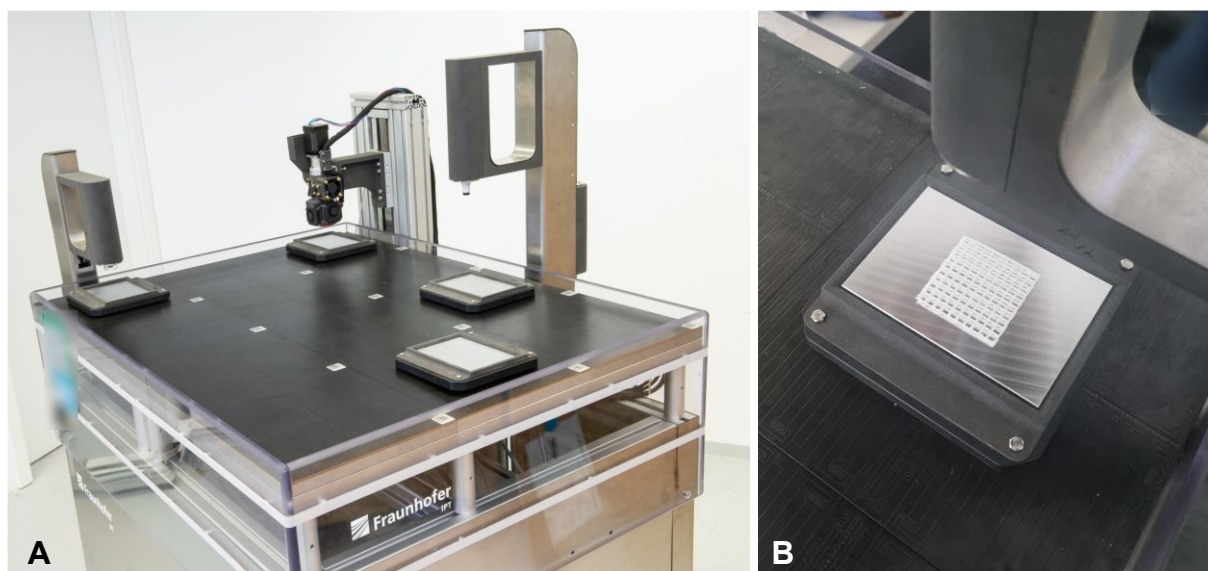


Figure 40: Laboratory setup of the imaging system (A) and a scaffold being imaged (B)

After the imaging step, based on the process instructions and the path planning algorithm, the mover is sent to its next station. The process integration and successful image acquisition are validated experimentally and presented in Chapter 5.1.2. Weaknesses of the concept and further research demands are discussed in Chapter 6.

3.6.3 Multi-agent Path Finding Algorithm for Dynamic Mover Control

Based on the fundamentals of decoupled production and MAPF in Chapter 2.5, an algorithm was developed that is tailored to the path planning requirements of the scalable production infrastructure for personalized scaffolds and the corresponding mover control. The developed algorithm can be categorized as an ICBS algorithm and combines the basic characteristics of conflict-based search with approaches from rule-based and random tree algorithms. Elements of the solver logic were inspired by the CBS algorithm for robotic path planning by Jin et al (Jin et al., 2023). Figure 41 describes the general integration of the MAPF algorithm for the collision-free control of multiple movers on a planar drive system.

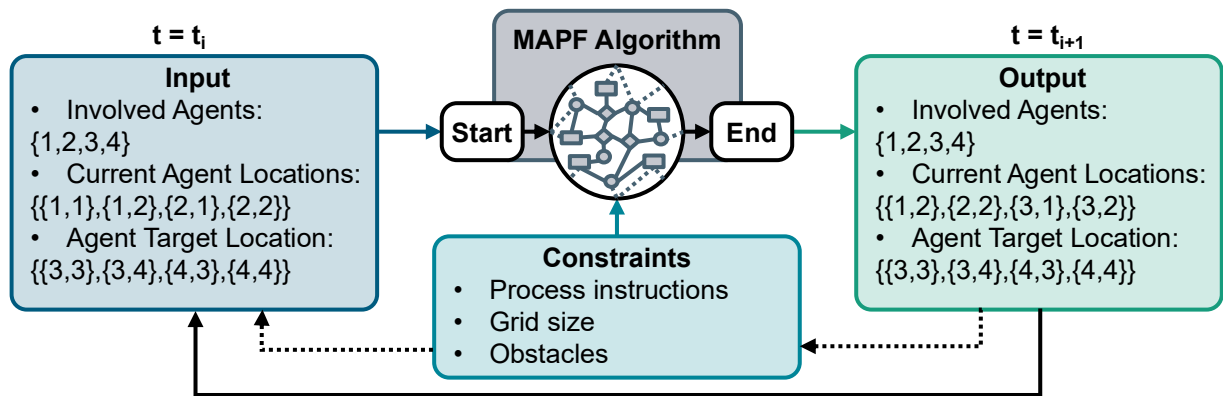


Figure 41: Input and output overview for the MAPF algorithm for mover control

There are multiple constraints that make this MAPF algorithm a sub-optimal, non-classical MAPF solver. After each planned and executed ideal path iteration, it is checked whether the *Agent Target Location* and the *Current Agent Location* match. If this is the case, the agent is decoupled from the process and its location is defined as an obstacle constraint. In the next iteration step, this agent is no longer listed in the *Involved Agents* array. The process instructions provide information about how long the agent remains in this state. This is the case, for example, when a mover reaches an extruder. The mover then executes its G-Code movements independently from the algorithm. Once this is complete, the process instructions array is read to determine the next process step. If this is, for example, moving to the imaging station, the corresponding target location is updated, and the mover is released again as an involved agent. The mover is then taken into account again in the next path planning iteration.

Figure 42 illustrates the logic of the algorithm to solve the MAPF problem. The algorithm begins with initiation (1) and thereby the parsing of the input data and the global constraints. Based on the current location of the agents and their target locations, the shortest possible paths are calculated (2). Since there is a possibility that several paths for an agent are equivalent, a random decision is made (3). Considering these ideal paths of all agents, it is checked where the agents will be in the next time step t_{i+1} (4). Thereby the conflict search is conducted, checking whether two agents would be at the same location at the same time (5). If there is no conflict, a rule-based approach is continued, where it is checked whether the mover would move back in the direction where it already was in the previous time step t_{i-1} (6). If this is not the case, the calculated path is confirmed and updated (7) to be executed next. If the mover were to move to its previous location, a randomization (9) would decide whether this path

would be released or redirected (8). If a redirection must be carried out for this reason or because a conflict has been detected, it is checked whether, in general, a movement in one direction is possible for the respective agents, or whether they are completely blocked (10). In this application, a mover has up to four options for leaving its position (right, left, front, back). If there is no completely blocking conflict for an agent and at least one free direction is navigable, the planned path is modified to include a change in one of the other directions (11). After that, the paths of all agents are checked again for conflicts (4).

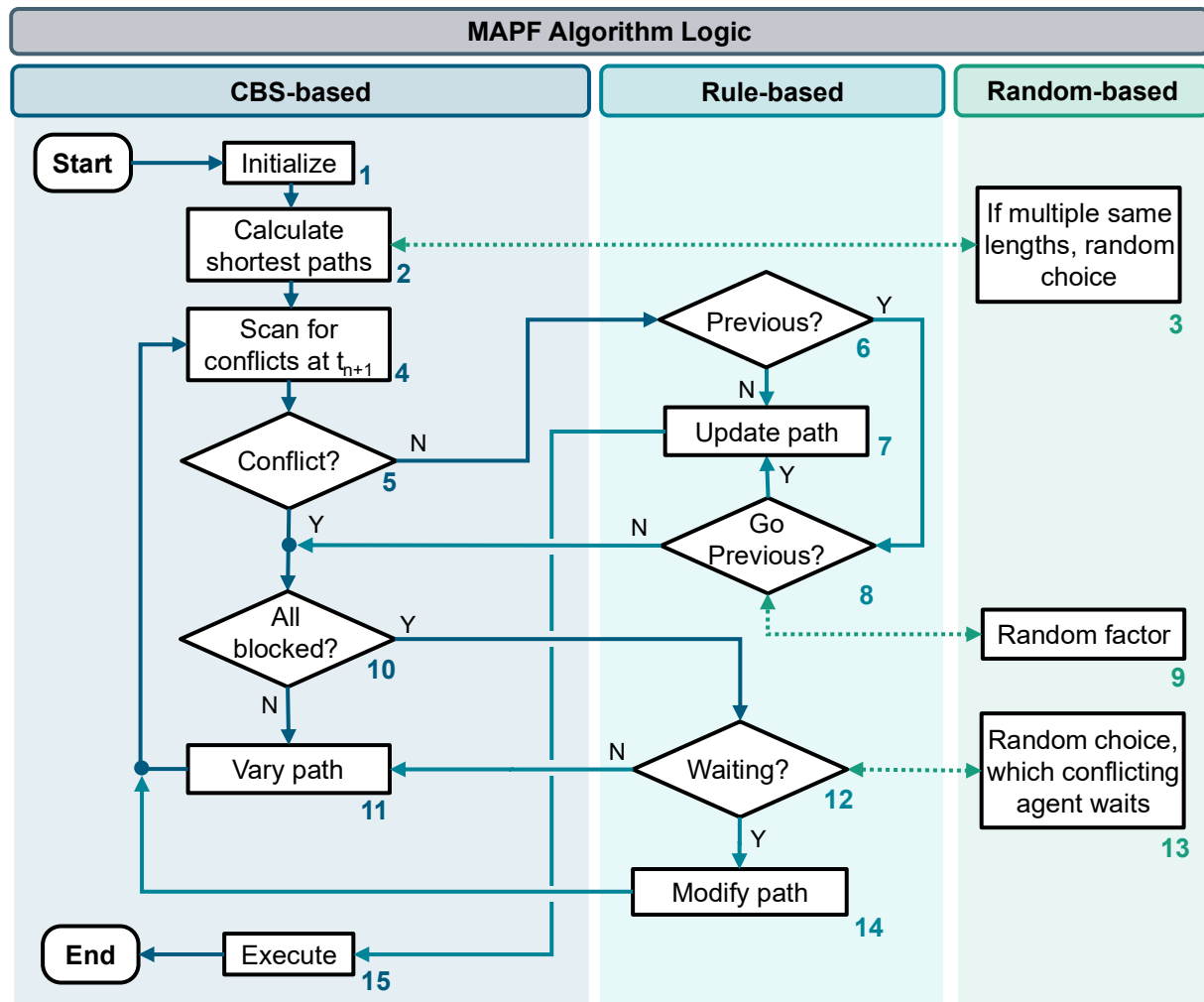


Figure 42: MAPF logic for mover control

In case a mover is not at its destination and all the directions it could move, are in conflict, a decision is made whether this mover should wait or whether the other mover in the same conflict should wait (12). This decision is made randomly (13). The paths are then modified accordingly so that one mover waits, and the other mover is allowed to move (14). Subsequently, a new scan is performed to determine whether all paths of all agents are conflict-free for the next time step (4). If this is the case and all agents have completed the algorithm, the iteration of the path planning is executed (15). This algorithm is then run in a cycle until all agents have reached their target and are therefore no longer listed in the involved agent's array for the algorithm. For validation on a hardware demonstrator, this algorithm was implemented in the PLC environment TwinCAT to control a four-mover planar drive system.

3.7 Set-up of a Demonstration System

To confirm the hypotheses derived from the research questions for the validation of the production concept, a demonstrator system is designed and constructed. The demonstrator is described as a Dynamically Interconnected Additive Manufacturing System (DIAMS), which is defined as an automated platform that uses dynamically interconnected agents between multiple additive manufacturing and control stations to enable parallel and flexible production. Figure 43 shows the computer-aided design (A and B) and the real system set up in the laboratory (C and D).

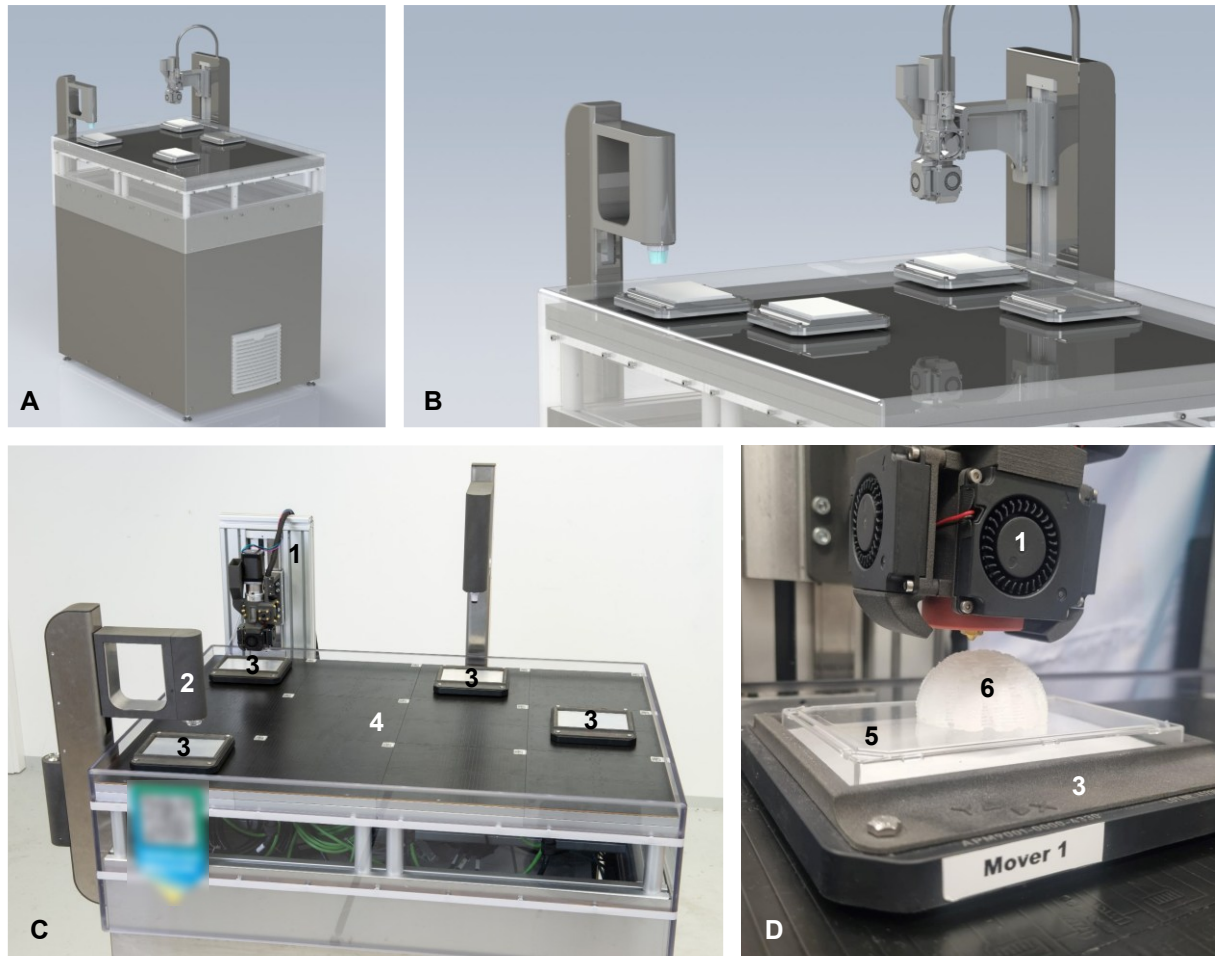


Figure 43: DIAMS demonstrator for validating the production infrastructure concept. A and B: Computer-aided design renderings, C: Laboratory set-up of the demonstrator, D: Close view on extruder, mover, substrate and printed scaffold. (Janning et al., 2025)

The system consists of a 3D printer extruder (1), a digital reflected light microscope camera for image recording (2) and the planar drive system (4) with four movers (3). The movers are equipped with the top lid of a standardized one-well plate made of polystyrene, which acts as the substrate (5). The scaffolds (6) are printed onto this substrate. The components are specified in Annex A.8 which summarizes all the components that were considered for the finalization of the production concept and later implemented for the construction of the DIAMS.

The planar drive, which consists of three times four tiles, each measuring 240 mm * 240 mm, can independently levitate four movers, each measuring 155 mm * 155 mm and position them planarly with a precision of up to 50 µm. The control cabinet for the planar drive is located below the planar drive. The camera and the extruder are each mounted on a motor-driven linear axis that is located on the side of the planar drive. The axis motors, as well as the end stop sensors, the extruder motor and its temperature sensor and its fans, are connected to the same control cabinet. All devices are controlled via the TwinCAT automation software. The MAPF algorithm presented in the previous chapter was implemented. A function for synchronous axis control was implemented in TwinCAT that reads the G-Code and extracts and transfers the corresponding coordinates to the axes of the planar and linear drive. By using the parameter set recommended by the extruder manufacturer, all hardware and software requirements for 3D printing are implemented. The DIAMS demonstrator is used to validate the individual technical approaches and to verify the developed concept for the production infrastructure, which is presented in Chapter 5.1.

3.8 Summary of Interim Results

In this chapter, based on the analyzed state of the art from Chapter 2, a concept for a holistically automated scalable production infrastructure for extrusion additive manufacturing of personalized medical scaffolds was systematically developed. This development process serves steps (C-E) of Ulrich's research methodology (Ulrich and Hill, 1976), compare Figure 5, and provides an application context relevant model, which is validated in Chapter 5.1. Methodically, the development approach, based on guideline VDI 2221:2019, included the following actions:

- Clarification of the requirements and characterization of the process
- Derivation of a function tree structure
- Selection of solution principles using the morphological box method and value benefit analysis
- Segmentation of the solution into realizable modules
- Elaboration of the modules and development of a demonstration system

Technically, the following results were achieved:

- A concept for a holistically automated scalable production infrastructure for medical scaffolds was developed and a demonstration system built, showcasing the key innovations.
- The integration of a magnetic planar drive for production intralogistics was elaborated for enabling a decoupled production.
- The use of a planar drive with frictionless levitating movers to realize the horizontal axis plane in 3D printing, was established.
- The integrability of different quality control stations was examined and developed for an inline imaging control for the detection of defects in the printed scaffolds.
- A conflict-based search algorithm for multi-agent path finding was developed and implemented on a four-mover planar drive system.

In summary and illustrated in Figure 44, based on the technical analysis of the EAM technology (1) in the state of the art, the PEAM concept was established (2). This concept was implemented and tested in the built DIAMS demonstrator (3). The demonstrator serves as a validation platform for the central technical features of the Scalable Production Infrastructure for Dynamically Interconnected Multi-agent EAM, for which the abbreviation SPIDA is introduced from here on (4).

The sub research questions **SRQ1 “Which process parameters of EAM influence the quality attributes of medical scaffolds and what are the technical and regulatory requirements for production?”** thus, can be answered with the harmonized catalog of regulatory requirements derived from the legislations in Chapters 2.3, and with the technical requirements derived in Chapter 3.1, based on the systematic literature review in Chapter 2.2.

The sub research question **SRQ2 “How can the process steps be automated for a scalable production of personalized scaffolds?”** can be answered with the development results of this chapter and concluding with the SPIDA concept. With the DIAMS demonstrator the

relevant tool is provided, to verify the answer to SRQ2 with proof of principle experiments, which are presented in the context of the validation in Chapters 5.1.

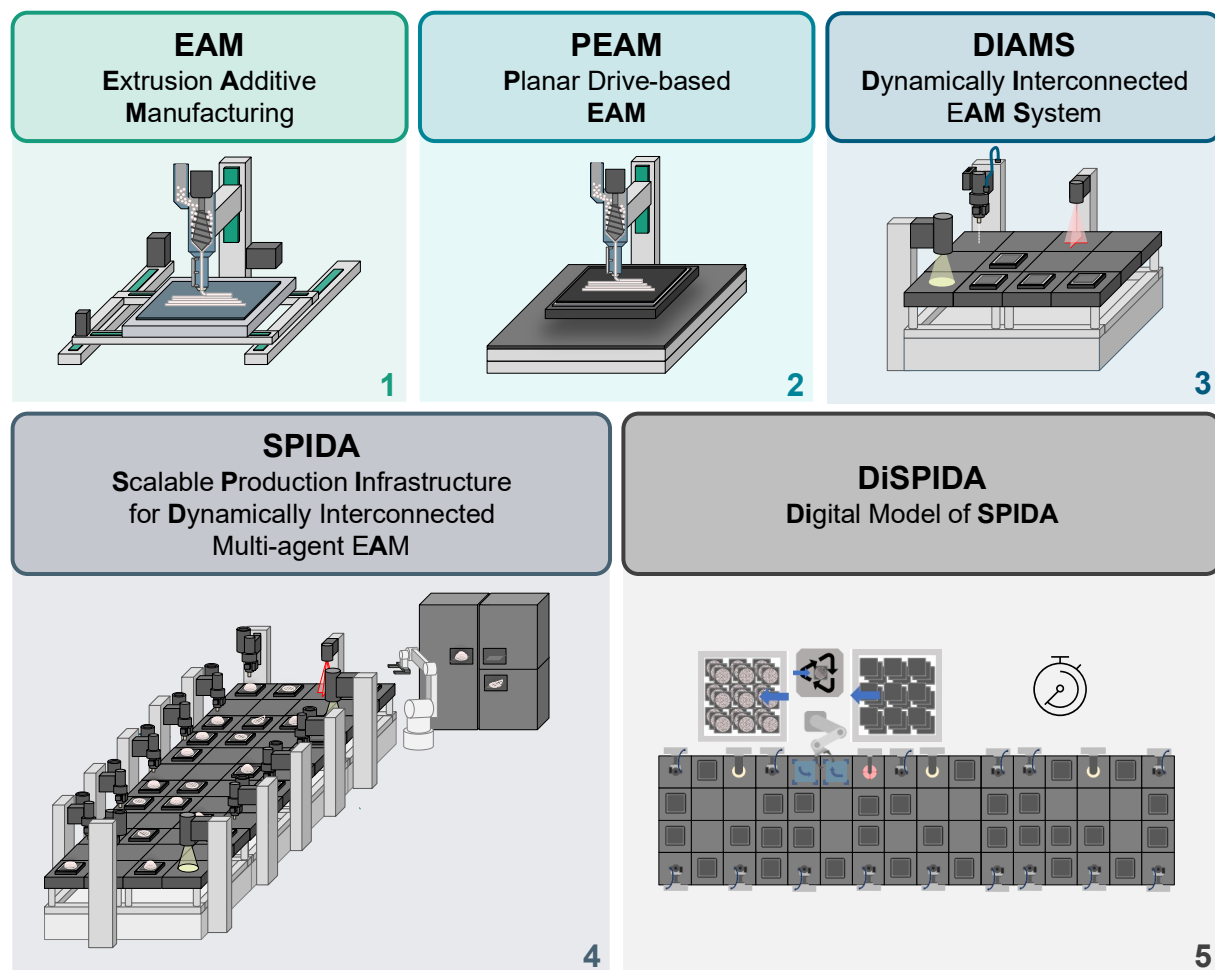


Figure 44: Overview of the system abbreviations

Since the DIAMS demonstrator can only represent the SPIDA production concept on a small scale, the results are not sufficient to be able to make statements regarding the scalability of the production infrastructure. However, since the scalability of production is a core aspect of the main research questions and the construction of larger demonstration systems for test purposes is not feasible, the scalability is being investigated using digital production models.

Digital production models can not only help with the planning of new production lines, but are also a valuable tool in quality management, as realistic models can be used not only to react to quality fluctuations, but also to predict for example production bottlenecks or downtimes. For this transition from reactive to predictive quality management and for the evaluation of scaling potentials, a digital representation is modeled on the basis of the SPIDA concept, which is referred to in the following as DiSPIDA (see Figure 43, (5)). For this purpose, the DiSPIDA base model is developed in the following chapter and then validated in comparative studies with the DIAMS demonstrator as a physical reference. Further simulation studies on scalability and optimization then provide the results to answer the sub research questions SRQ3 and SRQ4 and ultimately the main research question.

4 Digital Modeling of the Production Infrastructure

One focus of this work is the digital replication of the conceptualized production infrastructure for personalized medical scaffolds. The model, called DiSPIDA, can be utilized for planning production scale-up and for optimizing the use of resources like cleanroom space or required devices.

Figure 45 shows the methodological steps for developing the simulation model, described in this chapter. The figure is an extract of the overall methodology derived from Figure 23 and Figure 24. The modeling process is based on the three steps including preparation, formalization, and implementation according to VDI Guideline 3633:2018.

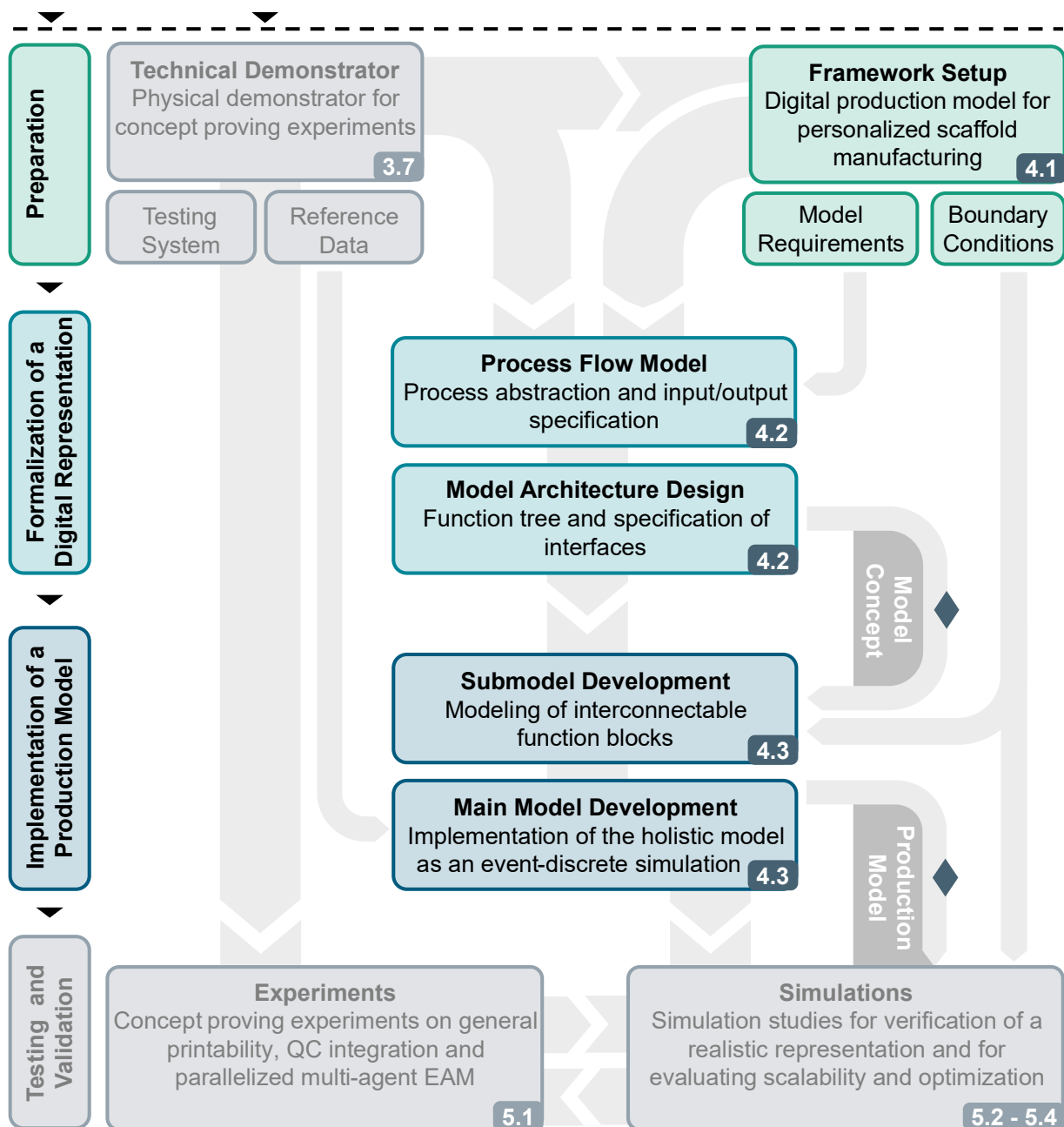


Figure 45: Methodology for developing a simulation model derived from VDI Guideline 3633

4.1 Preparation

In the following, the modeling process is prepared. Therefore, the production system designed in Chapter 3 is analyzed with regard to its core properties, for creating a digital model. The modeling objectives and boundary conditions are defined. Subsequently, a framework is outlined, which represents the most important interfaces and functions. Finally, the modeling environment is defined and JaamSim®, as an event-discrete simulation software, is introduced. The development then continues with the formalization of the processes. The developed production infrastructure for personalized scaffolds and the correspondingly constructed demonstrator form the subject of the digital representation.

Figure 46 shows a rough abstraction of the general process of the production infrastructure. First, the individual transport units, the movers, are prepared for printing a particular scaffold by interpreting the print job data and reserving the next processing stations. Secondly, the printing process for the first layer is carried out at one of the extruder stations. For the extruder to operate, it must be loaded with a sufficient amount of granulate. Preliminary investigations have shown that these extruder filling processes have no significant effect on the throughput times of scaffold production, which is why the extruder preparation step regarding granulate filling is neglected in the modeled production process. Further extruder preparations, such as replacing the printing nozzle or other consumables such as seals, take place outside the simulation periods and are neglected.

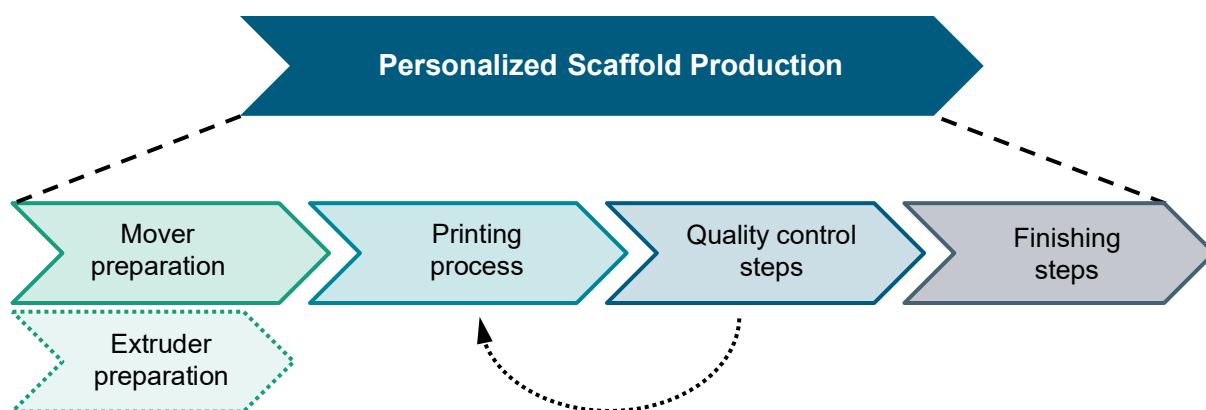


Figure 46: Basic abstraction of the personalized scaffold production process

Thirdly, depending on a predefined interval for quality controls, one or more control steps are carried out at regular intervals before the printing processes are continued. Lastly, multiple finishing steps are initiated. These involve detaching the printed scaffolds from the mover and, depending on whether the quality check is successful or unsuccessful, storing or disposing of them. If a print job was unsuccessful, it is repeated.

To reduce the complexity of the development of the production model, it is divided into multiple realizable modules. These submodels then fulfill individual subfunctions and are networked with each other in a framework, which is explained in the following.

4.1.1 Modeling and Simulation Objectives and Conditions

Three main objectives are pursued in the development of the simulation model. Firstly, the realistic simulation of the physical demonstration system. Secondly, the scalability of the model to increase production throughput. Thirdly, the usability of the model to optimize the production infrastructure.

Objective 1: Realistic Digital Representation of the Demonstrator

The demonstrator resulting from Chapter 3.7 for the developed production infrastructure for individual scaffolds is to be realistically reproduced in the form of a digital model.

This model therefore consists of the submodels described in Chapter 4.1.2: “Extruder”, “Planar Drive”, “Applicator”, “Separator”, “Computer” and the quality control stations “Imager” and “Scanner”. Figure 5 shows the general layout of the demonstrator (left) and the corresponding visualization in the simulation environment (right).

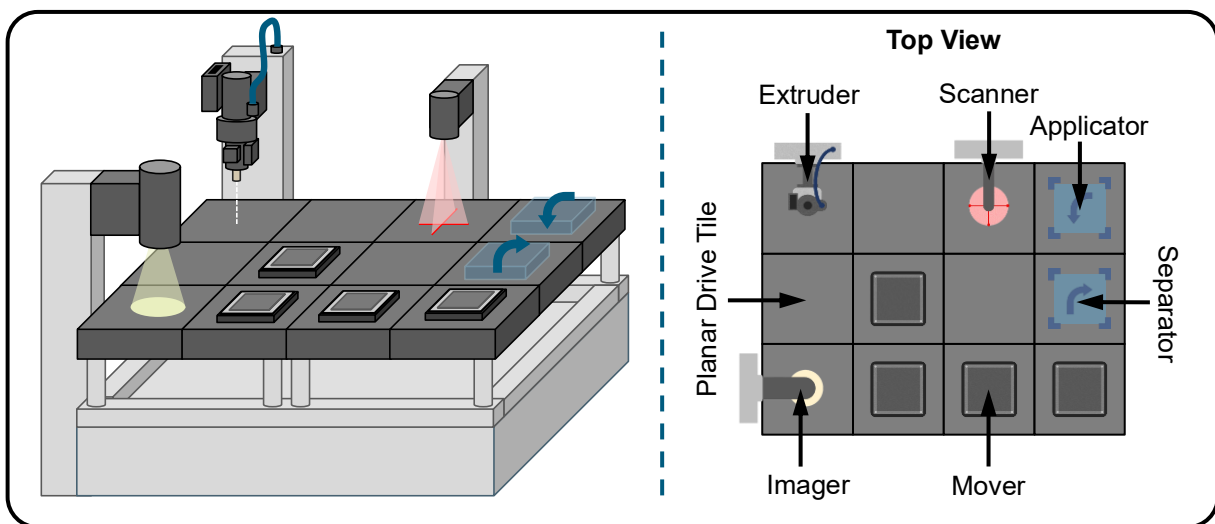


Figure 47: Digital representation of the demonstrator with its submodels. Left: General demonstrator layout. Right: Visualization in the simulation environment.

Objective 2: Model Scalability for Increased Throughput Simulations

The simulation model developed, based on the demonstrator, should be scalable in a modular way in order to increase the throughput of scaffolds produced. This involves flexibly expanding the layout by increasing the number of tiles of the planar drive and adding further movers, extruders or QC stations inside the simulation model. The model can then be used to relate the production throughput to the involved resources like clean room space or required devices.

Figure 48 qualitatively represents the hypothesis that there is not necessarily a linear relationship between the production area used and the throughput achieved. These correlations are examined using the simulation model, compare Chapter 5.3.1.

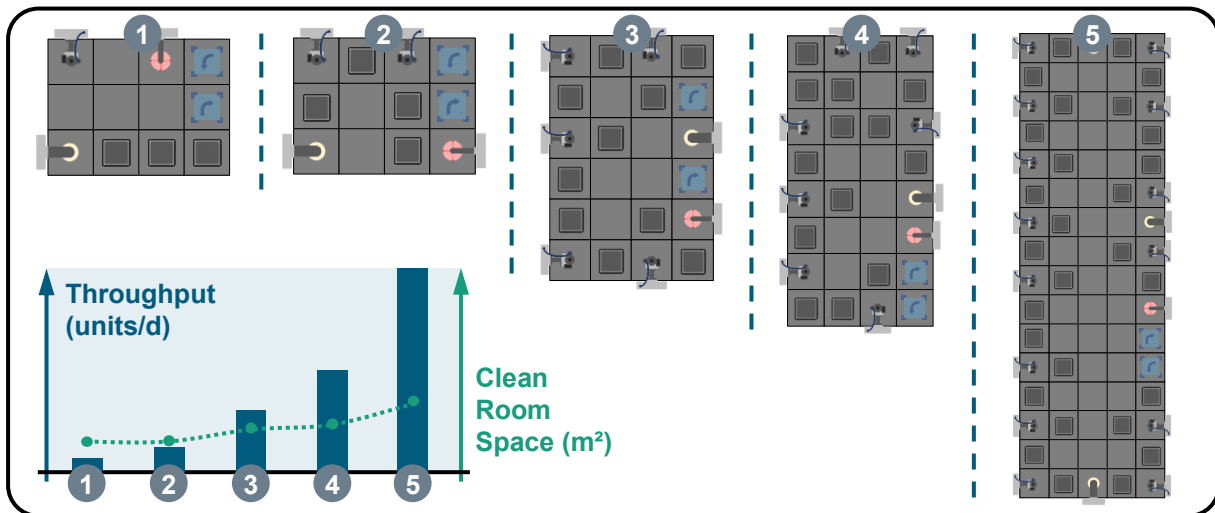


Figure 48: Schematic representation of the scaling of the production model to compare throughput and required cleanroom area.

Objective 3: Model Adaptability for Layout Optimization

The simulation model can be adapted in different ways. On the one hand, the configuration, for example the number of interacting movers and extruders on a specific area, can be adapted. On the other hand, the layout itself, for example the arrangement of the individual stations or the planar drive tiles, can be adapted. The model can be used to simulate different scenarios and collect data. This data can then be used, for example, to optimize the production throughput per mover or to optimize economic parameters like the return on investment per mover, which is qualitatively visualized in Figure 49 and discussed in Chapter 6.

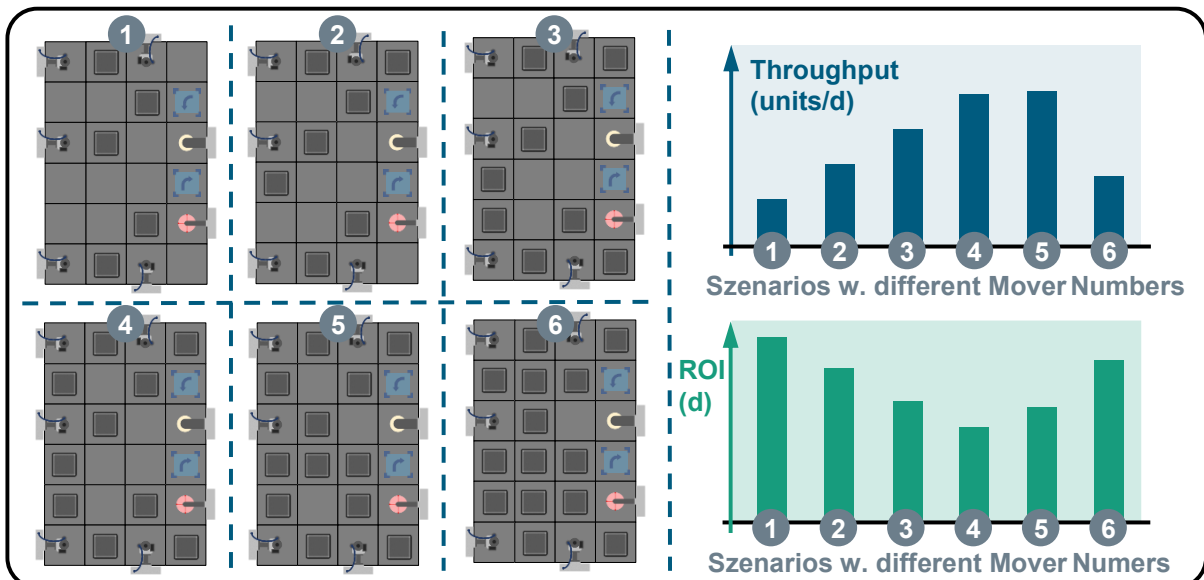


Figure 49: Schematic representation of different mover configurations and its impact on production throughput and the date of the Return on Investment (ROI).

Modeling and Simulation Conditions

Multiple boundary conditions are defined to implement these modeling objectives. These include conditions and assumptions that affect the simulation objects, and the simulation process itself. Since the production infrastructure is specifically designed for personalized objects, the individualization of the simulation entities must be addressed. For this purpose, the reference scaffold is based on the geometry of half an ellipsoid, which is fully parameterized by the diameter and height. The volume of the basic geometry of the scaffold, required to calculate the print material, is thus obtained from Equation 1. These two parameters are randomly assigned in a normal distribution for the generation of individual scaffold geometries. To do this, a mean value and a standard deviation must be specified for each.

$$V_{Scaffold} = 0,5 \cdot \frac{1}{3} \cdot \pi \cdot h_{Scaffold} \cdot d_{Scaffold}^2 \quad (1)$$

$V_{Scaffold}$: Volume of the enclosing scaffold geometry

$h_{Scaffold}$: Height of the scaffold

$d_{Scaffold}$: Diameter of the scaffold base

Since this geometry is 3D printed as a scaffold, the object consists of layered filament grids and not of solid material (compare Figure 50 and Figure 51). The height of these individual layers is determined by the nozzle diameter. The layer height is generally set to 50 % of the nozzle diameter. The porosity of the scaffold is realized by the mesh spacing, i.e. the distance between the individual filament paths. Porosity thus also describes the ratio between the volume of the scaffold's basic geometry and the volume of the material printed (compare Equation 2).

$$P_{Scaffold} = 1 - \frac{V_{Material}}{V_{Scaffold}} \quad (2)$$

$V_{Material}$: Volume of printed material

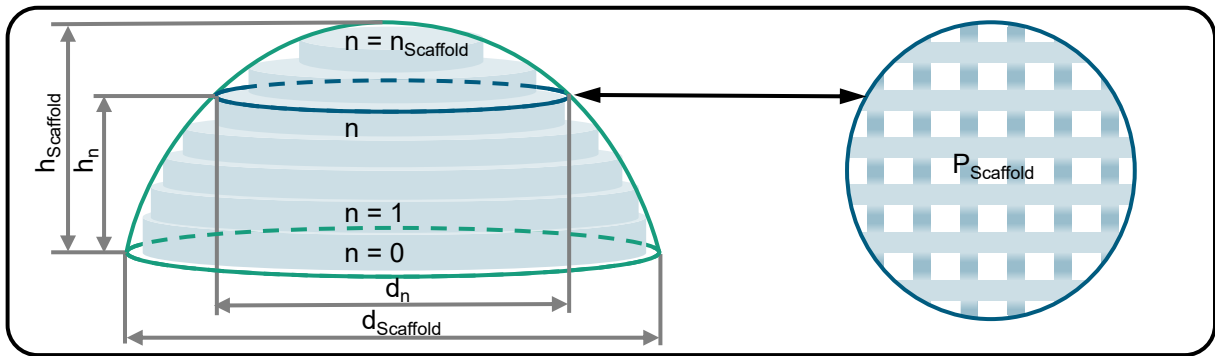


Figure 50: Schematic representation of a scaffold reference body as a half ellipsoid with the defining dimensions and a schematic sectional view of the inner mesh structure.

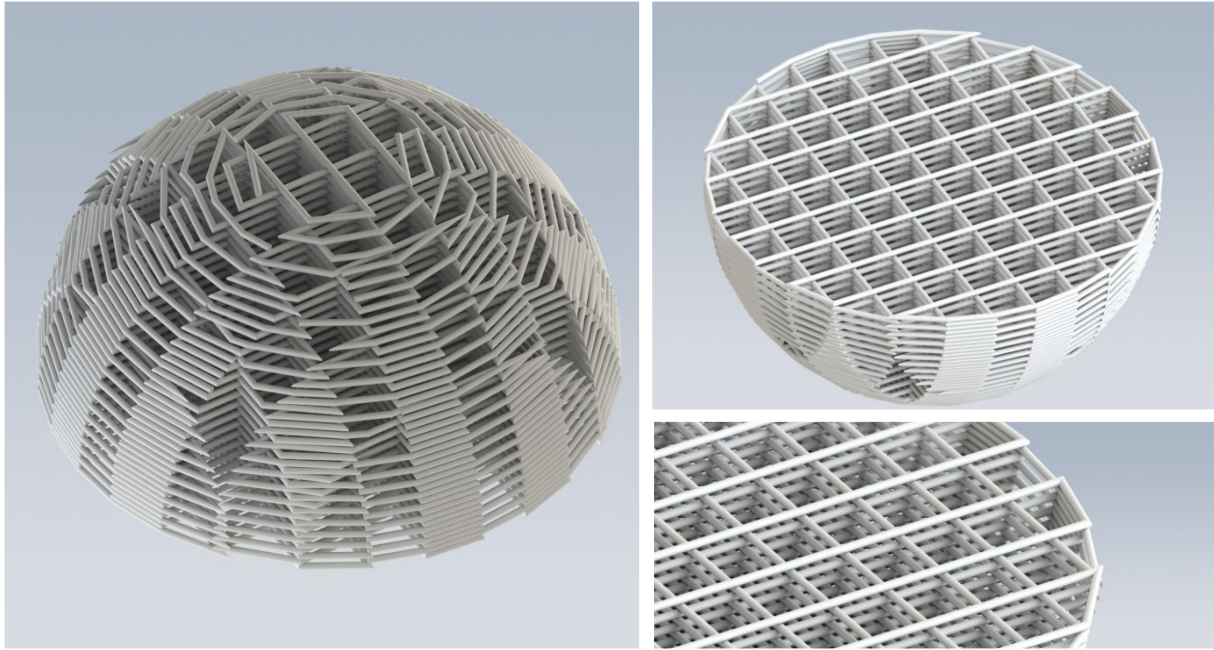


Figure 51: Rendering of the CAD model of the test scaffold for illustration purposes. Scaffold height: 25 mm, scaffold diameter: 50 mm, filament thickness: 400 μm .

These parameters including the exemplary assumed values for a reference scaffold are listed in Table 9 and need to be implemented in the model via a configuration file.

Table 9: Assumptions regarding the scaffolds as the central simulation entity of the production model

Parameter	Symbol	Assumption	Unit
Scaffold Height Mean	$h_{Scaffold,Mean}$	38	mm
Scaffold Height Minimum	$h_{Scaffold,Min}$	30	mm
Scaffold Height Maximum	$h_{Scaffold,Max}$	70	mm
Scaffold Height Standard Deviation	$h_{Scaffold,SD}$	20	mm
Scaffold Diameter Mean	$d_{Scaffold,Mean}$	105	mm
Scaffold Diameter Minimum	$d_{Scaffold,Min}$	70	mm
Scaffold Diameter Maximum	$d_{Scaffold,Max}$	135	mm
Scaffold Diameter Standard Deviation	$d_{Scaffold,SD}$	20	mm
Layer Height	h_{Layer}	200	μm
Scaffold Porosity	$P_{Scaffold}$	99	%

These parameters have a direct influence on the time needed to print a layer. This printing time is approximated based on the volume of each single layer and the porosity of the scaffold. The volume of a single print layer as a function of its height inside the scaffold is given by Equations 3 to 7.

$$n_{Scaffold} = \frac{h_{Scaffold}}{h_{Layer}} \quad (3)$$

$$dn = \left(d_{Scaffold}^2 - \left(d_{Scaffold} \cdot \frac{n}{n_{Scaffold}} \right)^2 \right)^{\frac{1}{2}} \quad (4)$$

$$V_n = \left(\frac{d_n}{2} \right)^2 \cdot \pi \cdot h_{Layer} \quad (5)$$

$$V_{Material,n} = V_n \cdot (1 - P_{Scaffold}) \quad (6)$$

$$t_{Print,n} = \frac{V_{Material,n}}{\dot{V}_{Print}} \quad (7)$$

$n_{Scaffold}$: Number of printing layers required for a scaffold

n : Number of an individual layer within the scaffold

h_{Layer} : Layer height

d_n : Diameter of an individual layer within the scaffold

V_n : Volume of the slice of an individual layer within the scaffold

$V_{Material,n}$: Volume of printed material for an individual layer within the scaffold

$t_{Print,n}$: Printing time required to complete an individual layer

$\dot{V}_{Print}$: Material extrusion rate of the printer

Parameters such as the extrusion rate are parameterized separately for each extruder (compare Chapter 4.4). Further assumptions concern the simulation and the defined use case itself. A runtime of 6 days (144 h) is set for the simulations performed. This value is based on typical automated production environments, where weekly continuous operation with one day for cleaning and maintenance is planned. This duration is set as the simulation runtime but can be adjusted as required. Due to the randomized scaffold geometries and the resulting variance in processing times, five replicates are created for each simulation, with the randomization seed varying. This prevents individual anomalies from distorting the comparison of different scenarios. Also, due to this randomization factor for the production of individual scaffolds, the production can no longer be modeled deterministically. Accordingly, a dynamic, stochastic, discrete event-controlled simulation method is chosen for implementation.

4.1.2 Submodel Framework Set-up

Figure 52 shows in more detail which functions must be modeled in order to be able to represent the respective process steps realistically. The individual functions are assigned to individual submodels, which are responsible for the execution of the respective functions. The framework therefore consists of the following submodels:

Computer

Receives the production order of an individual scaffold and generates a print job, which is then linked to an available mover. Initiates the substrate application step.

Applicator

Receives a mover with a print job and applies a substrate onto which the scaffold will be printed. Initiates the printing process.

Extruder

Receives a print-ready mover and reads information about the print job. It determines how many layers have already been printed and which layer currently needs to be printed. The printing time is not determined from real data from, for example, a G-Code file, but is simulated based on the individual parameters of the print job. A definable cool-down time must elapse between the printing of two layers. During this time, the mover is sent back to its home position. Once the time has elapsed, the printing of the next layer or the conduction of a quality control step is initiated. The intervals for conducting quality control steps are configurable (for example: *Imaging every 5 layers*). In addition, after each layer has been printed, a randomized decision is made whether the layer was printed successfully or failed. The probability of failure can be configured (for example: *Failure:Success = 1:10000*).

Quality Control

Receives a mover with a partially or fully completed scaffold. A test is simulated that decides whether a layer defect is detected, whether a layer defect is not detected, or whether a non-existent defect is detected as a defect. The sensitivity and specificity of a quality control test is configurable. A quality control submodel can exist in different variants, for example to perform regular in-line checks or to carry out final end product inspections. Possible variants of the quality control submodel that are relevant for the application are:

- **Imager** for the geometric inspection of individual print layers
- **Scanner** for three-dimensional inspection of the external dimensions of the product
- **Tomograph** for three-dimensional inspection of the internal morphology of the product
- **Scale** for the gravimetric inspection of the product weight
- **Press** for the mechanical inspection of the product's compression properties

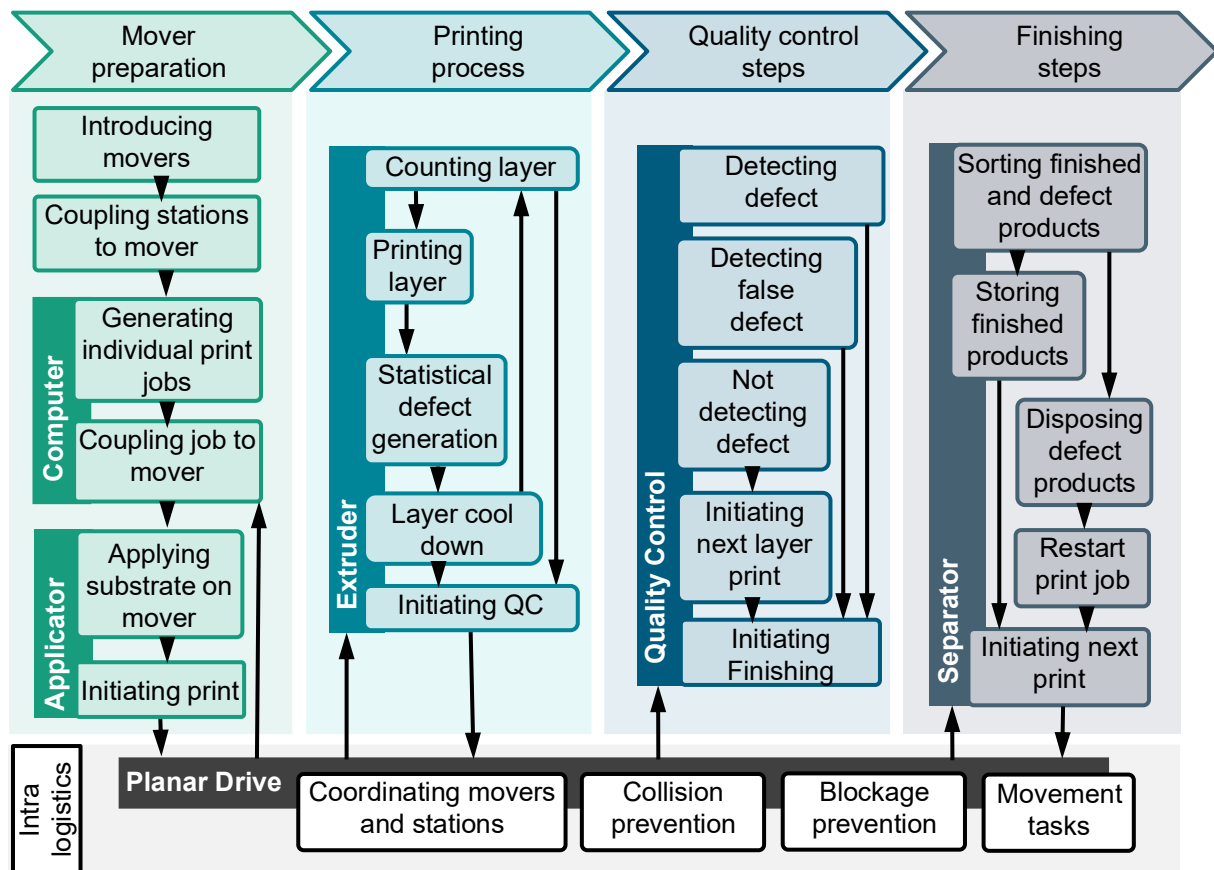


Figure 52: Classification of the functions required to realize the production process to individual submodels

Separator

Receives a mover with a finished scaffold or one that has been identified as defective. Finished scaffolds are separated from the mover, stored and all process times are logged. The mover is released to receive a new print job. Defective implants are separated and disposed, whereby the corresponding print job is decoupled and restarted with the same mover.

Planar Drive

Acts as an intralogistics transport system and, analogous to the real planar drive, consists of several tiles connected together. A tile receives a mover, reads the current destination station of the mover, identifies the tile on which this station is located and determines the tile to which the mover is passed to next in order to minimize the distance to the target tile. At the same time, corresponding algorithms are used to prevent collisions with other movers and the formation of deadlocks (see Chapters 2.5 and 3.6.3). When a mover reaches its target tile, it is handed over to the appropriately connected station, where, for example, a print or a control step is carried out.

On the same level as the submodels, two further functions have to be fulfilled. Firstly, the movers are introduced into the system. The movers are modeled as containers that can hold a print job entity carrying all the information about a scaffold order. This print job also generates a phantom entity that represents the current state of the scaffold to be manufactured. Also, the mover container holds a substrate entity, which is defined as a requirement for starting a printing process.

The progression of a mover through the individual submodels is outlined in Figure 53. The figure shows the successful completion of a scaffold print. If one of the quality control submodels detects a defect, the separator reinitiates the job, instead of logging the finished job. The damaged scaffold including substrate is discarded. In both cases, the released mover can then proceed through the process again.

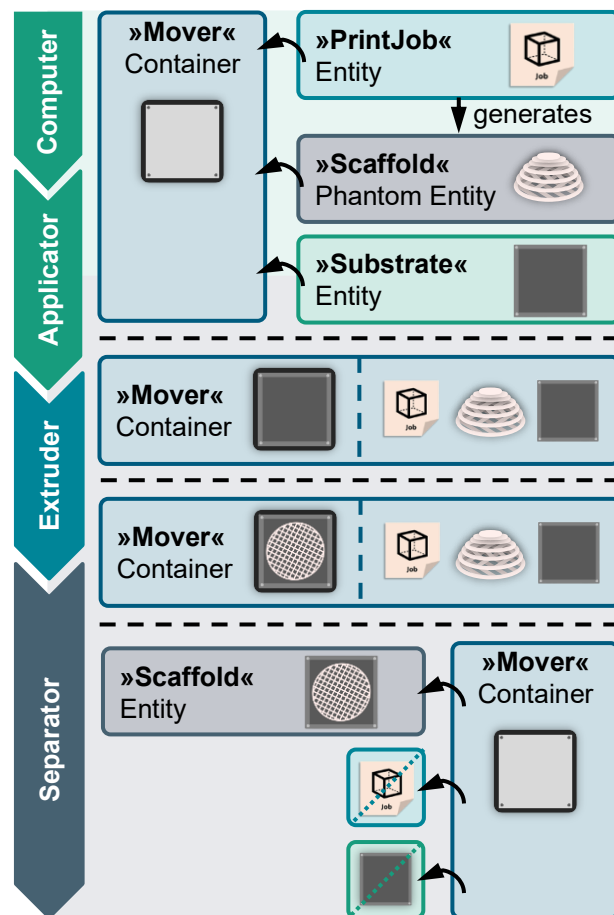


Figure 53: Mover entity development stream

In addition to the introduction of the movers into the model, secondly, they must be coupled to multiple stations. For each mover, a home position on one of the tiles of the planar drive must be defined. This has technical reasons, one of which is that in the event of a detected deadlock, an automatic reset must be carried out, which requires that the movers can deviate from their current target position to a fixed defined alternative position, which cannot force the movers into another deadlock. Also, the home positions of the movers serve as defined start and end points for the process.

Also, it can be optionally specified whether a mover permanently serves a specific extruder or imager, or whether it always selects the next possible free station. The first setting has the advantage that the potential paths, movers have to travel during the process, can be more easily minimized by placing the movers' home positions and the extruders close together. This can actively prevent the mover paths from crossing frequently, which would lead to increased evasion maneuvers and potentially to longer downtimes. Another reason for actively coupling the movers to specific stations relates to the medical application and the traceability of material with according batch records (compare requirements P1 and D4 in Chapter 2.3). Using multiple extruders for one implant increases the number of granulate batches involved which increases difficulty to trace a defect cause down to a specific batch.

4.1.3 Discrete-event Simulation Using JaamSim

The software JaamSim was chosen to implement a discrete-event simulation of the described application. The main reason for specifically choosing JaamSim is the open-source transparency and the suitability for logistics and production-related applications (Lang et al., 2021). The described production system with the multi-layer 3D printing processes in combination with several control processes can also be abstracted as an assembly system. Due to the characteristics of a decoupled multi-agent platform, realized by the planar drive, the system can be compared to Dynamically Interconnected Assembly Systems (DIAS) (Göppert, 2022). For modeling and scheduling in DIAS, it has already been shown in previous work that discrete-event simulation, in particular using JaamSim, is suitable (Göppert et al., 2018).

Compared to other open-source DES like Salabim and CloudSim, JaamSim offers the largest library of pre-defined standard objects, functions and classes for building simulation models, which are applicable for this manufacturing use case. The ability to create submodels that can be combined into a complete model is another necessity due to the complexity of the modeled production infrastructure.

4.2 Formalization

Figure 54 shows the submodels as function groups and the simulation entities introduced in Chapter 4.1.2 with their interdependencies. The following chapter formally describes the logical processes within the individual submodels which are then practically implemented in the JaamSim DES.

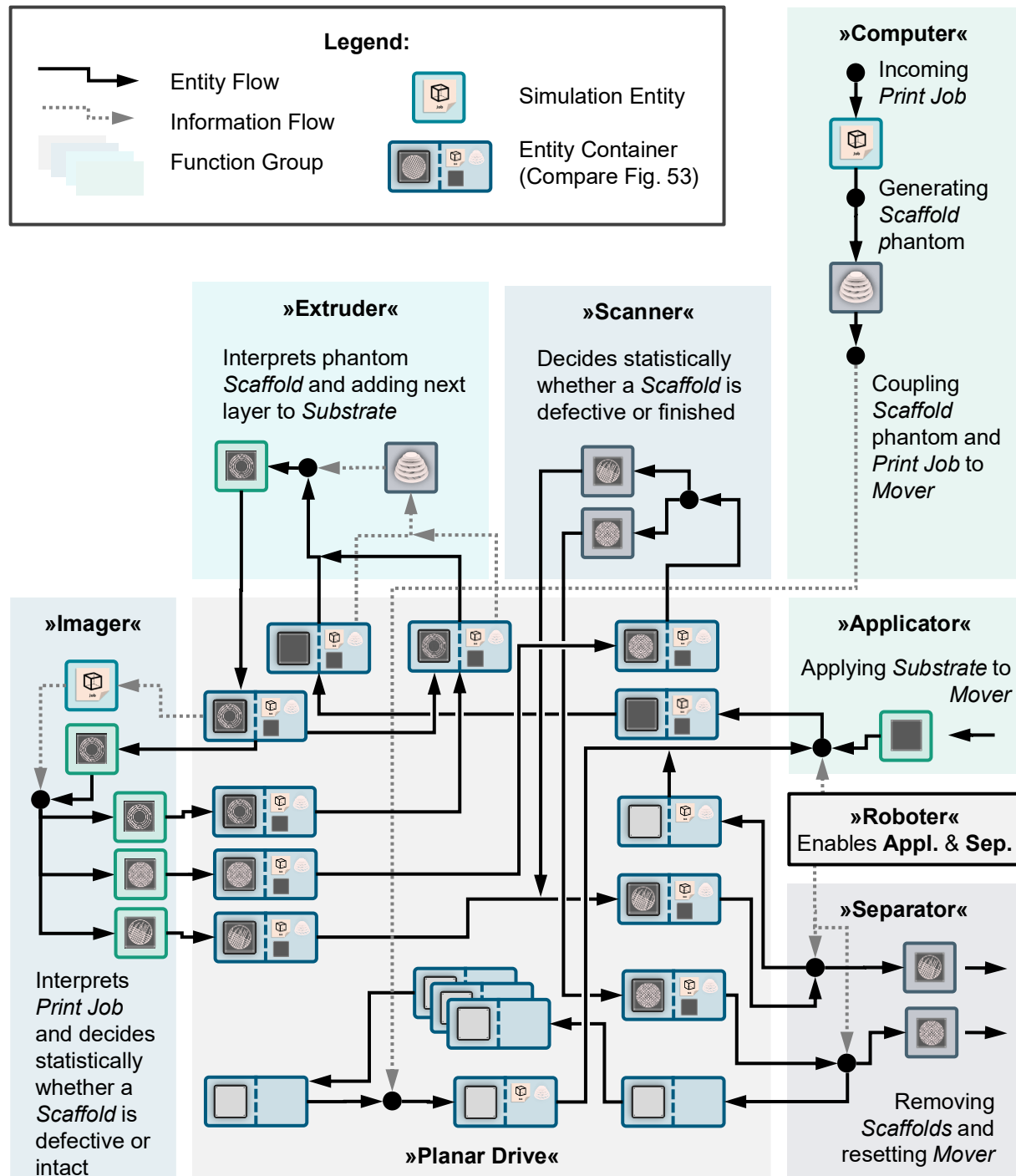
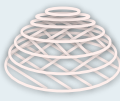
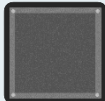
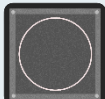
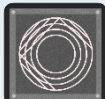
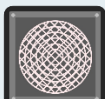


Figure 54: Top layer flow chart visualizing the connections between the different submodels and the overall implementation approach in JaamSim. Individual symbols are specified in Table 10

In the **Computer** submodel, individual print jobs, as introduced in Chapter 4.1.2, are generated. This generates a phantom scaffold, carrying the information for the scaffold to be produced. This print job and phantom scaffold are then coupled to the first available mover. This triggers the process of the mover moving on the planar drive to the **Applicator** submodel. There, a substrate is robotically placed from a storage location onto the mover. The robot acts as a resource that must be available for this application to run. Different submodels can access this resource, although the robot can only execute one job at a time. The next process step involves the mover moving to the **Extruder**, which reads the data from the phantom scaffold and initiates the printing process of the first layer. Accordingly, the appearance of the simulation entity changes, compare Table 10.

Table 10: Legend of the simulation entities and their possible states

				
Print Job	Phantom Scaffold	Mover	Substrate	Mover with Substrate
				
0 % Printed Scaffold	10 % Printed Scaffold	20 % Printed Scaffold	30 % Printed Scaffold	40 % Printed Scaffold
				
50 % Printed Scaffold	60 % Printed Scaffold	70 % Printed Scaffold	80 % Printed Scaffold	90 % Printed Scaffold
				
100 % Printed Scaffold	Failed Print	Finished Scaffold on Substrate without Mover	Defect Scaffold on Substrate without Mover	

Consequently, the mover moves to its home position to wait for a period of time defined as the cool-down time. After that, the mover moves to the extruder again to print the next layer. A configuration file is used to specify how often an inline quality control (IQC) should be performed. For example, if the QC interval is set to five, an IQC, in this case an imaging process, is carried out after every fifth print layer. An error rate can be configured for the printing process, with the result that the scaffold is declared defective with a defined probability each time a layer is printed. In addition, test sensitivity and specificity can be determined for the IQC. This results in the possibility that a scaffold that has been declared defective is not detected as defective. Also, a scaffold declared as not defective can be incorrectly detected as defective. In the event that a defect is detected, the mover moves to the **Separator**, where, analogous to the applicator, the substrate, together with the scaffold printed up to that point, is removed and the simulation entity is thus deleted. The mover must then return to the applicator to repeat the print job with a new substrate. In the event that a print job passes through completely without a detected defect, a final inspection is initiated, in this case a scan at the

Scanner submodel. Finally, a process for storage is carried out at the separator, analogous, as with a defective scaffold. In this process, the data of the completed scaffold is logged, the simulation entities are deleted, and the mover is reset and sent to the home position so that new print jobs can be assigned. The described overall process can be dynamically conducted in multiple instances simultaneously in parallel. For this, multiple movers must be available on the planar drive and multiple print jobs must be waiting in the queue.

For the implementation of the processes, the individual simulation entities carry different information. This information is stored in the form of attributes. These attributes are listed in Table 11 and are described hereinafter.

Table 11: Attributes of the simulation entities and their functions

Line	Attribute	Default	Function
Print Job (SimEntity)			
1	Type	"PrintJob"	Class
2	ScaffoldHeight	'0 [mm]'	Personalizable parameter
3	ScaffoldDiameter	'0 [mm]'	Personalizable parameter
4	Index	0	Chronological index of Job
6	ResponsibleMover	0	Mover number of coupled mover
7	MissPrints	0	Number of previous fails of this job
Phantom Scaffold (SimEntity)			
1	Type	"Scaffold"	Class
2	RequiredLayers	0	Number of layers required for scaffold
3	QualityStatus	"DefectFree"	Documentation of the scaffold quality
Substrate (SimEntity)			
1	Type	"Substrate"	Class
2	PrintedLayers	0	Number of layers already printed
Mover (EntityContainer)			
1	Type	"Mover"	Class
2	ScaffoldHeight	'0 [mm]'	Print Job attribute
3	ScaffoldDiameter	'0 [mm]'	Print Job attribute
4	Index	0	Print Job attribute
5	QualityStatus	"DefectFree"	Print Job attribute
6	RequiredLayers	0	Phantom Scaffold attribute
7	PrintedLayers	0	Substrate attribute
8	MoverNumber	0	Individual number of the mover
9	MoverStatus	"Available"	Availability of the mover
10	QCCount	0	Layer counter for next QC step
11	CoupledExtruderNumber	0	Extruder this mover is coupled to
12	CoupledImagerNumber	0	Imager this mover is coupled to
13	CoupledScannerNumber	0	Scanner this mover is coupled to
14	TargetTileXY	'{0,0}'	Coordinates of tile the mover targeted
15	TileDeltaX	0	Current and targeted tile X difference

16	TileDeltaY	0	Current and targeted tile Y difference
17	NextTileToGoXY	'{0,0}'	Coordinates of tile mover moves next
18	NextTileToGoNumber	0	Index of tile mover moves next
19	CurrentTileNumber	0	Index of current tile mover is on
20	PreviousTileNumber	0	Index of tile mover was on before
21	WaitCount	0	Counter of periods a mover had to wait in case of deadlocks

The **Print Job** has the attribute *ResponsibleMover*, which initially has the value 0 as long as no mover has been assigned to the job. If an available mover has been coupled, the attribute takes the mover number as its value. The *MissPrints* attribute is a counter that counts how often the print job had to be repeated due to a detected defect. This attribute is used to prioritize movers with a higher *MissPrints* value so that the time required to complete the job is as short as possible.

The **Phantom Scaffold** simulation entity has the *RequiredLayers* attribute, which is an integer value and is calculated from the *ScaffoldHeight* of the *PrintJob* and the configured layer height. The *QualityStatus* of the *Phantom Scaffold* can be given different strings. The default state is “DefectFree”. There are also the states “UndetectedDefect”, “DefectDetected”, “FalseDefectDetected” and after a successful final inspection “Passed”.

The **Substrate** entity carries the attribute *PrintedLayers*, which is a counter that is increased by one after each successful printing process at the extruder and until this value corresponds to the *RequiredLayers* value.

In comparison to the other simulation entities, the **Mover** is a container entity that can accommodate other simulation entities and accept their attributes. However, the mover itself can also have other attributes. The *MoverStatus* can accept the default string “Available” when it is ready to accept a print job or various other states that describe the current task, such as “WaitingForMover”, “WaitingForExtruder”, “Printing”, “Moving” etc. The *CoupledExtruderNumber* specifies the extruder that the mover serves. This prevents the mover from selecting a different free extruder for each layer if several extruders are available. Is this set to 0, the mover selects the next available extruder. The *CoupledScannerNumber* and *CoupledImagerNumber* attributes can also be used to assign a mover to a specific station. *TargetTileXY* is an attribute that is relevant for movement on the Planar Drive. Each station, for example an extruder, is connected to a specific tile of the planar drive system (compare Figure 55). After a mover has passed through a process step, it is assigned a new target. This target is described by the X and Y coordinates of the corresponding tile on the planar drive. The attributes *TileDeltaX* and *TileDeltaY* each indicate the difference between the tile coordinates on which the mover is currently located and the target coordinates. *NextTileToGoXY* specifies the coordinates of the next neighboring tile to which the mover is steered. *NextTileToGoNumber* specifies the numeration of this same tile. *CurrentTileNumber* and *PreviousTileNumber* specify the numeration of the current or previous tile on which the mover is or was located. The *WaitCount* is a technical attribute to prevent deadlocks, which is explained in more detail in the description of the planar drive submodel in Chapter 4.3.2.

Figure 55 shows the interconnection of the individual submodels as a supplement to Figure 54. The individual models developed in JaamSim are independent models that have one input and at least one output. The inputs and outputs of submodels can be linked with each other in order to implement cross-submodel models.

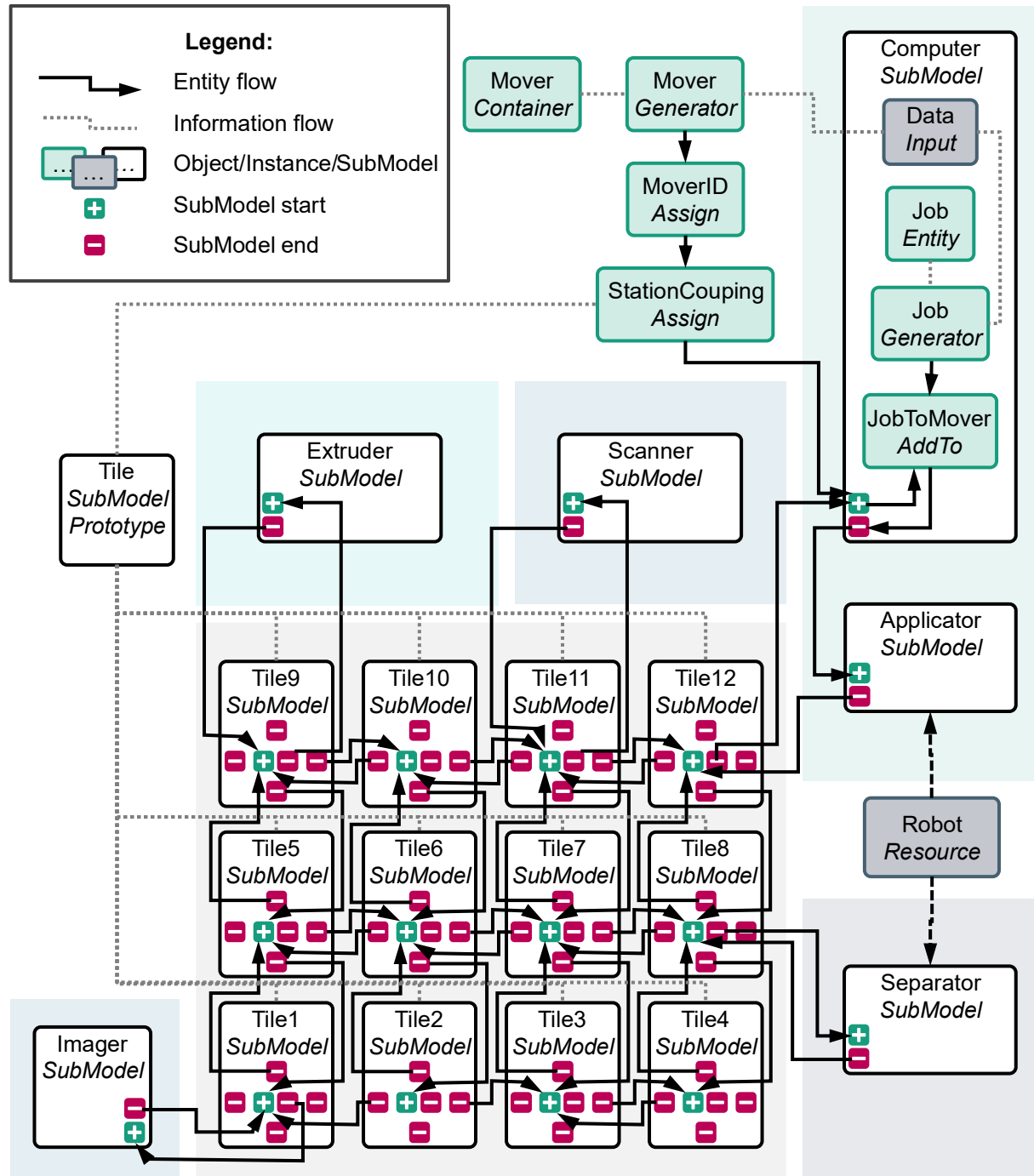


Figure 55: Connections of the inputs and outputs of the individual submodels.

The submodels **Computer**, **Applicator**, **Separator**, **Extruder**, **Scanner** and **Imager** are introduced in Chapter 4.1.2 and are each similarly structured with one input and one output. The initial generation and preparation of movers takes place outside a submodel on the first architectural layer of the main model. Another notable aspect is the **Robot** instance, which is not

modeled as a submodel or simulation entity, but as a resource that is available to other submodels. A resource can be blocked and released again when triggered by according processes.

The central and most complex element of the model is the ***Planar Drive System***, which is a composition of many individual ***Tile*** submodels that are connected to each neighbor tile and optionally another station submodel. The information flow connects to a master tile, also described as the *Tile SubModelPrototype*. This construct is relevant for model scalability. A master tile is relevant because the individual tiles have an identical structure and function in the same way but still have to execute different tasks simultaneously in parallel with communication between the tiles being still required. This enables the tiles to handle their private attributes, which have to be overwritten during the process flow, independently, while its public attributes are carried centrally by the master tile and can be overwritten by all tiles. These processes are explained more specific in the description of the implementation of the ***Tile*** submodel, compare Chapter 4.3.2.

4.3 Implementation

The formally described model is implemented in the discrete-event simulation environment of JaamSim. JaamSim offers numerous function blocks, some of which are used for the model implementation. These are shown in Table 12 and are generally described in Table 13.

Table 12: Function blocks utilized for the implementation of the production model

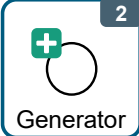
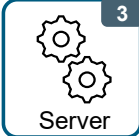
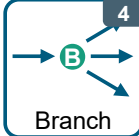
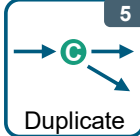
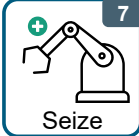
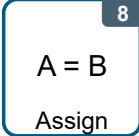
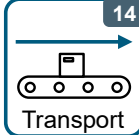
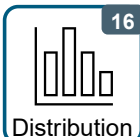
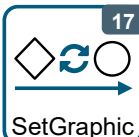
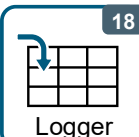
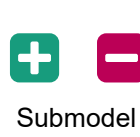
 1 Delete	 2 Generator	 3 Server	 4 Branch	 5 Duplicate
 6 Release	 7 Seize	 8 Assign	 9 AddTo	 10 Remove
 11 Assemble	 12 Delay	 13 Gate	 14 Transport	 15 FileToMatrix
 16 Distribution	 17 SetGraphic	 18 Logger	 19 Queue	 20 Submodel Start/End

Table 13: Description of the function blocks used for model implementation

Number	Name	JaamSim Description
1	Delete	Destroys any entity it receives.
2	Generator	Creates copies of a prototype entity at specified intervals.
3	Server	Processes a received entity over a specified duration.
4	Branch	Directs a received entity to a selected destination.
5	Duplicate	Sends copies of the received entity to a set of destinations.
6	Release	Releases one or more units of a resource.
7	Seize	Seizes one or more units of a resource.
8	Assign	Assigns new values to attributes.
9	AddTo	Add entities to an existing EntityContainer.
10	Remove	Removes some or all of the entities from an EntityContainer.
11	Assemble	Combines subcomponents to create an assembled part.

12	Delay	Delays a received entity by a specified duration.
13	Gate	Blocks received entities from progressing further until the EntityGate is opened by one or more Thresholds.
14	Transport	Transports a received entity along a specified path at a fixed speed.
15	FileToMatrix	Populates a two-dimensional array with data from a specified file.
16	Distribution	Provides a selection of standard theoretical probability distributions as well as user-defined probability distributions.
17	SetGraphic	Changes the appearance of the received entity.
18	Logger	Records the outputs and state data for a generated entity in an output log.
19	Queue	Stores received entities until they are needed.
20	Submodel Start/End	The first/last component of a submodel

The following chapters present the implementation of the individual submodels and explain their functionality. The structural approach is to first present the simplified simulation flow diagram for each submodel, which is based on the real implementation in JaamSim. Thereafter the function blocks used are briefly described in tabular form. Finally, the interfaces to other submodels are explained.

The complexity of the implementation has been reduced in the descriptions in order to increase the clarity of the main logical processes. The actual implementation, including all configurations, is made available with the details in Annex A.11.

4.3.1 Individual Print Job and Mover Preparation

The **Computer** submodel is presented in Figure 56. In the submodel, the processes start from two paths and then converge. Firstly, *PrintJob* Simulation entities are generated within the submodel (1). The frequency of job generation can be freely configured to simulate the incoming orders according to the use case. The job entities are then assigned their *ScaffoldDiameter* and *ScaffoldHeight* parameters (2). For this purpose, the mean, maximum, minimum and standard deviation values are read from an input file and stored into a matrix in JaamSim (3). A statistical normal distribution is then used to generate a random value from this data (4), which can then be assigned to the job parameters. This ensures that each job is individual, enabling to simulate the individualization of the production. Further individualization parameters can be added. The jobs are then transferred to a gate including a queue, where the job waits until a signal is activated that a mover is available to receive the job (5). As soon as this trigger is activated by a ready mover, a job is let through the gate, resulting in this job and this mover getting linked to each other via an assignment (6). A delay (7) is implemented to ensure that the assignment of the mover is completed before the next assignment is carried out. In the following assignment (8), the mover reserves the *Applicator* station, sets its *TargetTileXY* attribute to the coordinate array of the *Applicator* and sets its *MoverStatus* to “busy”. The mover

container, which enters the submodel, is then loaded with the job using the *AddTo* function block (9). The mover container, including the job, is duplicated (10), whereupon the information of the duplicate, such as *ScaffoldHeight* and *ScaffoldDiameter*, is processed and a new simulation entity, the phantom scaffold, is assembled with the attributes *RequiredLayers* and *QualityStatus* (11). The phantom scaffold is then loaded into the other duplicate of the mover container (12). In the last assignment, the attributes of the individual entities in the container are then transferred to the mover.

The *Computer* submodel is structurally integrated sequentially between any *Tile* submodel and the *Applicator* submodel. Accordingly, the input of the *Computer* submodel is connected to the exit output of a *Tile* and the output of the *Computer* submodel to the input of the *Applicator*.

Table 33 in Annex A.10 provides an overview of the individual function blocks and a brief description of their respective function to supplement the figure of the submodel.

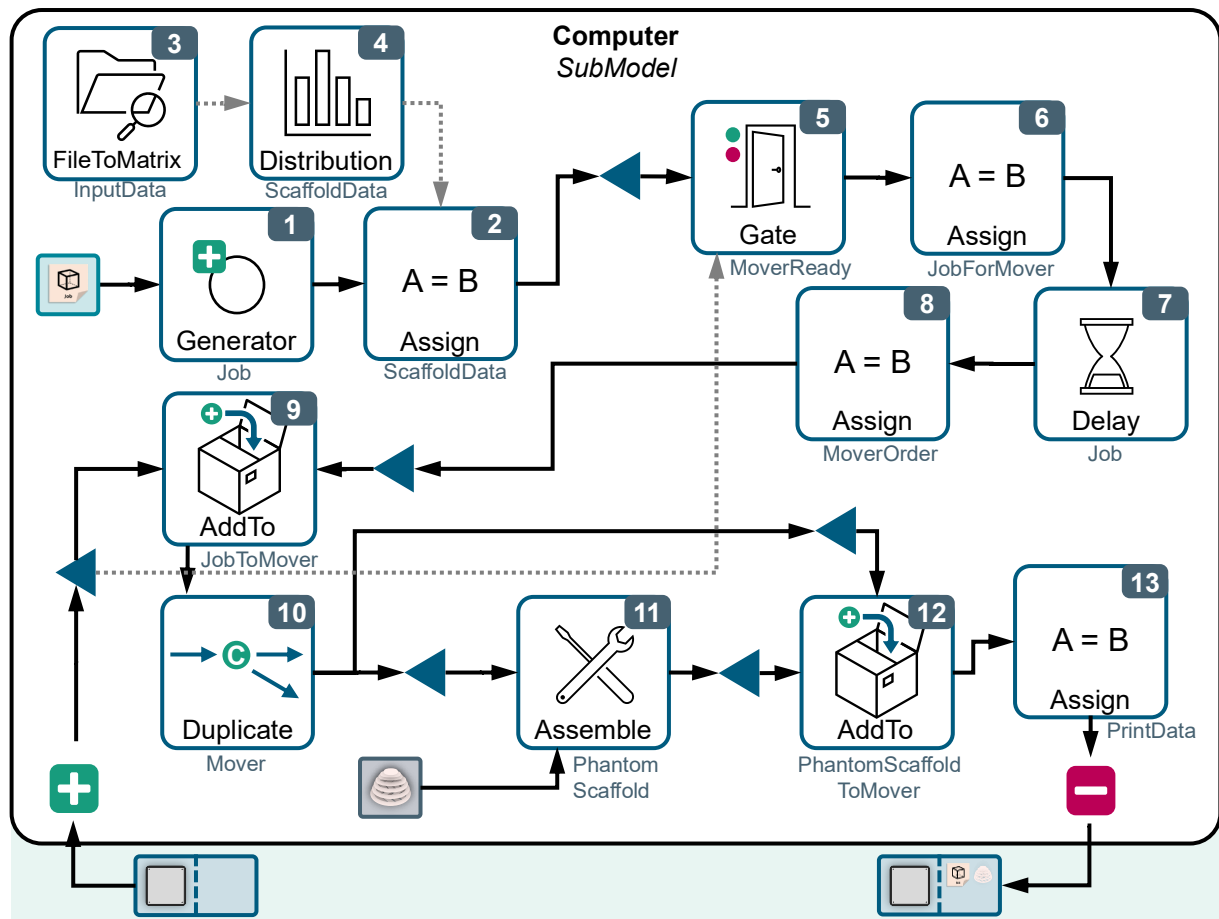


Figure 56: Simulation flow diagram of the *Computer* submodel

The *Applicator* submodel is presented in Figure 57. Within the submodel, substrate simulation entities are generated (1) and entered into a queue. The number of generated substrates can be configured to simulate the number of substrates available in the storage, according to the use case. Analogous to the *Computer* submodel, the substrates wait in front of a gate until a signal is triggered that a mover is ready for loading (2). The mover is then reserved for the substrate (3). Then the *Robot* resource is seized (4) and a transport step is executed that

simulates the movement of the substrate from the storage to the mover (5). After the transportation step has been completed, the *Robot* resource is released again and can be used for other processes. The gate signal is reset (7) and the substrate entity is loaded into the mover container (8). Accordingly, the graphic of the mover container is adjusted to visualize the loaded substrate (9). A delay of two seconds is added to simulate the mounting time between mover and substrate (10). Finally, the mover is assigned its new target (11). To do this, the *TargetTileXY* Array is overwritten with the coordinates of a tile at which an extruder is located. If multiple extruders are available, the mover is assigned to the extruder that is serving the fewest movers so far.

The *Applicator* submodel is structurally integrated sequentially between the *Computer* submodel and any *Tile* submodel. Accordingly, the input of the *Applicator* submodel is connected to the output of the *Computer* submodel and the output of the *Applicator* is connected to the input of any available *Tile*.

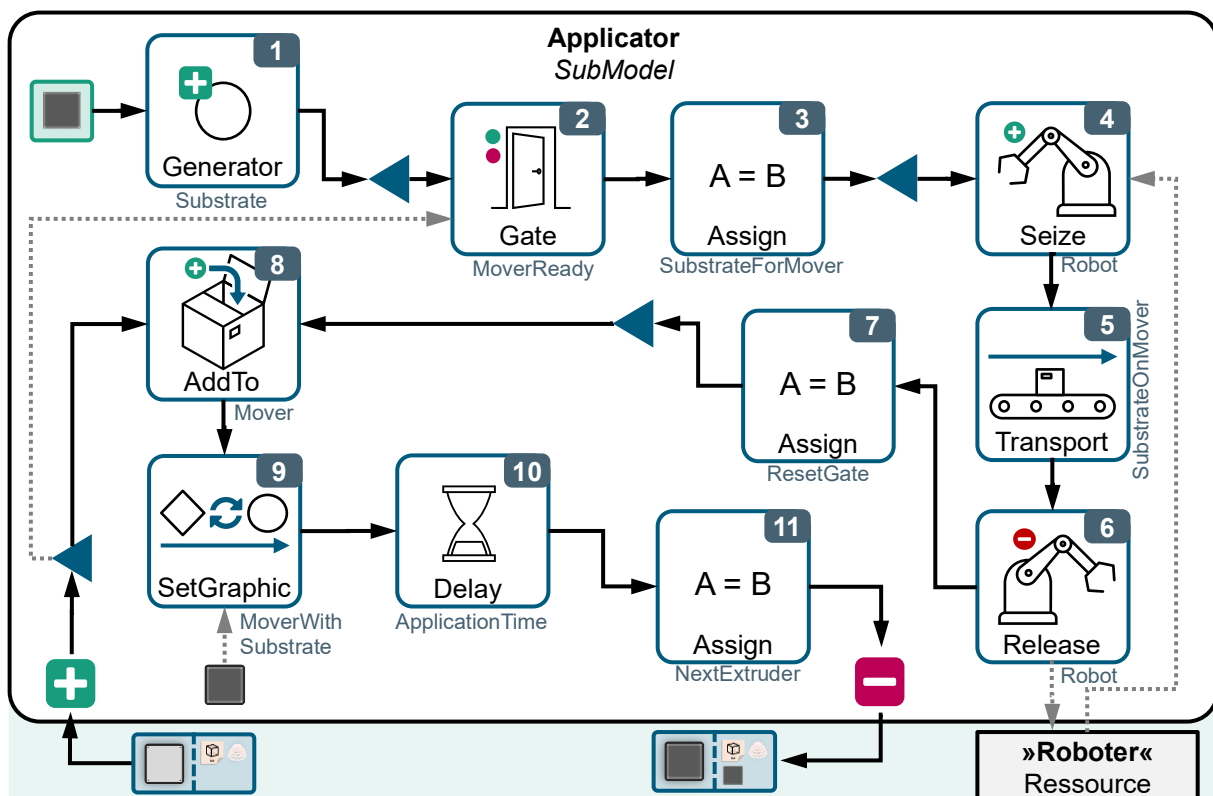


Figure 57: Simulation flow diagram of the *Applicator* submodel

Table 34 in Annex A.10 provides an overview of the individual function blocks and a brief description of their respective function to supplement the figure of the submodel. Detailed information on the programming of the individual function blocks can be accessed via Annex A.11.

4.3.2 Movement of Individual Entities Using a Planar Drive Approach

The planar drive is the most complex element of the modeled production infrastructure, since it has to simultaneously coordinate multiple individual objects in terms of timing and location. The modeling was based as closely as possible on the physical model, both in terms of the modular form and the control algorithms to solve the MAPF problem.

The following section shows first the modular structure of the planar drive system model and the interconnection of the individual submodels. Thereafter, the attributes of the *Tile* submodel are described in more detail, after which the simulation flow diagram is explained.

Figure 58 shows the general structure of the **Planar Drive** model. The individual submodels each have one model input and five model outputs. Four of these outputs lead to the left, right, front or back neighboring tile inputs. Not all outputs have to lead to another input, instead can also lead to an open end. These four outputs enable the transport routes from one tile to another. The fifth output serves as an exit and allows a mover on a tile to virtually leave this tile and enter the submodel of a station, for example an extruder. The input of a *Tile* can be linked to several different outputs of other tiles or stations at the same time. The numbering of the tiles is based on a predefined coordinate system, where the *Tile* number first increases in the positive X direction and then in the positive Y direction. In addition to the numbering, all tiles are declared with an X/Y coordinate pair, where the first number of the coordinate array defines the X coordinate and the second the Y coordinate.

The scaling of the planar drive surface is realized by connecting further tiles. This theoretically allows for infinite scaling, neglecting computational boundaries. In addition to rectangular arrangements of the tiles, a more specialized form of the planar drive surface is also possible, for example in an L- or U-shape. Tiles that are to be permanently blocked can also be assigned the status “obstacle”. These tiles are then ignored during path planning.

All *Tile* submodels are clones of the **Tile SubModelPrototype** and are permanently linked to it. The *SubModelPrototype* acts as a master and passes on all its attributes to its clones. It should be noted that the general attributes are to be understood as public shared attributes, which can be overwritten by a tile during the simulations and then change for all tiles simultaneously. This is relevant, for example, when a mover on a *Tile* triggers an assignment that causes a *Tile* to be declared as “Blocked”. This is then realized by the attribute *TileStatusArray* of the prototype *Tile* writing the string “Blocked” at the appropriate spot inside the array. This is then automatically transferred to all other tiles and in subsequent processes, corresponding reactions occur. In contrary to the public attributes, the *Tile* prototype also has private attributes, which are referred to as custom outputs. Although these are inherited by the clones, each tile clone can overwrite these values privately without the values changing for the other clones. This is relevant for the automatic numbering of the tiles, as well as for the automatic reading of the individual coordinates of the tiles. Without these private attributes, for example, it would not be possible for a mover to determine which *Tile* it is located on, as all *Tile* clones would carry the identical information and would be indistinguishable from one another. These attributes and custom outputs are explained further in Table 14 and its description.

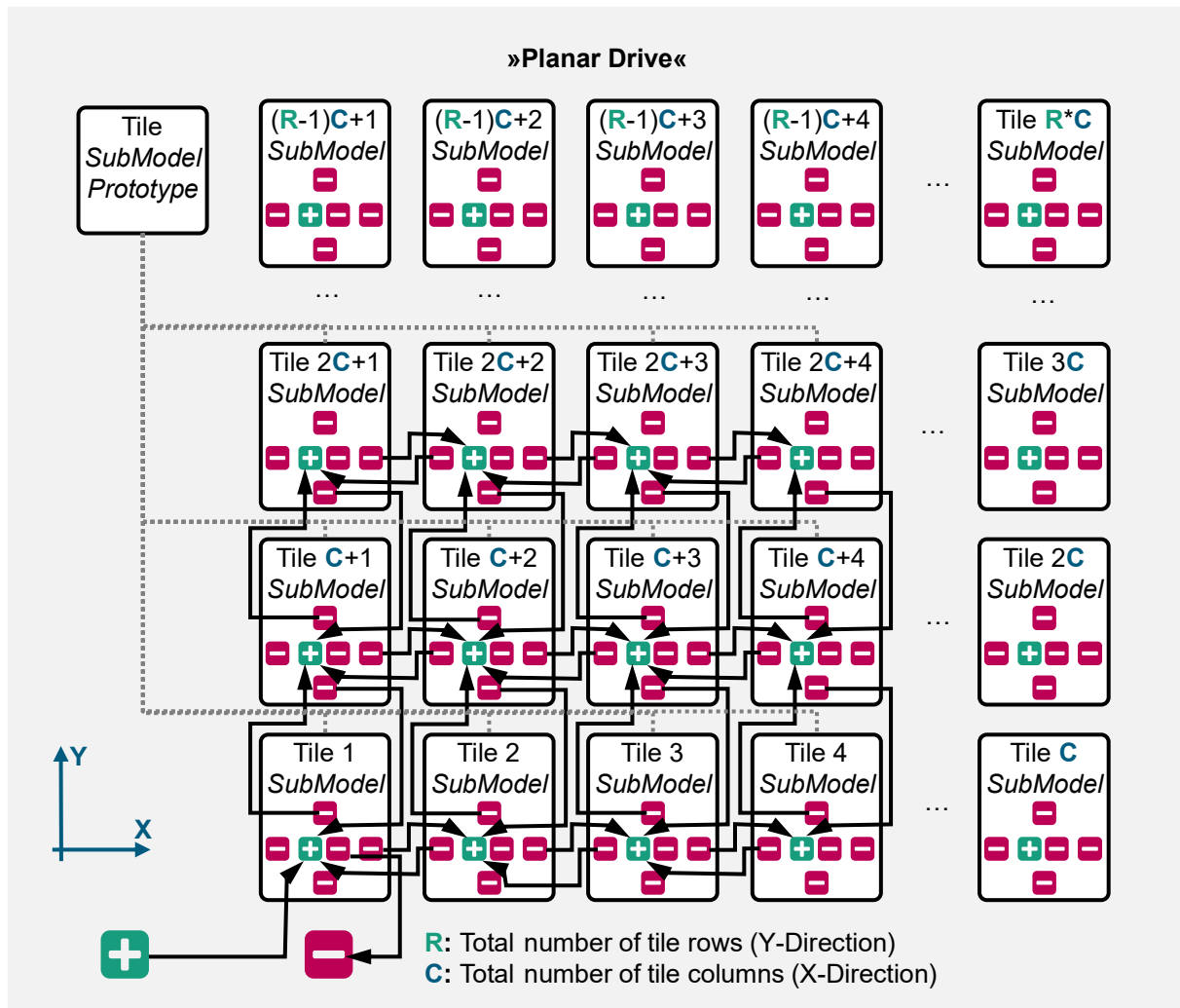


Figure 58: Structure of the planar drive model as a modular, scalable construct of multiple interconnected tile submodels

The attributes of the *Tile* prototype in Table 14 are divided into attributes that must be set manually once for the configuration of the model (marked in blue) and attributes that are written and read automatically during the simulation.

The *TileArray*, contains the individual coordinates of each *Tile*. Whereby the position within the array corresponds to the *Tile* numbering. The *TileStatusArray* contains the status of each *Tile*. *MoverHomeTiles* is an array that specifies the home *Tile* of the respective mover. Whereby the position within the array corresponds to the mover numbering. *MoverTargetTiles* is an array in which the *Tile* coordinates currently declared as the target for the respective movers are stored. *MoverStationReservation* is an array in which the current station coordinates, declared as the destination for the respective mover, are stored. *MoverAvailabilityArray* is an array in which it is stored whether a mover is "idle" or "busy". The *ExtruderTiles*, *ImagerTiles*, *ScannerTiles*, *ApplicatorTiles*, *SeparatorTiles* are each arrays in which the positions of the respective stations are stored. The *ExtruderServingMoverAmount*, *ImagerServingMoverAmount* and *ScannerServingMoverAmount* are arrays that each store the number of movers assigned to a station. Whereby the position within the array corresponds to the station numbering. *TileRows*

and *TileColumns* specifies the size of the planar drive aggregate in terms of tile amount. *MoverTravelSpeed* specifies the speed at which a mover moves between the tiles.

The custom output *TileNumber* is defined by a function that first creates a substring from the name of the individual tile, e.g. “Tile1”, which consists of the characters from the fifth digit onwards, so that only the number of the tile clone is kept. Secondly, this string is parsed to a number so that the function ultimately assigns a number for each clone. The custom output *TileCoordinatesXY* uses the same function and thus its own *TileNumber* to access its coordinates in the *TileArray* of the prototype *Tile*.

Table 14: Attributes of the *Tile PrototypeSubModel* with definitions for the demonstrator model

Line	Attribute	Default Definition
1	<i>TileArray</i>	'{ { 1,1 }, { 2,1 }, { 3,1 }, { 4,1 }, { 1,2 }, { 2,2 }, { 3,2 }, { 4,2 }, { 1,3 }, { 2,3 }, { 3,3 }, { 4,3 } }'
2	<i>TileStatusArray</i>	'{"Free","Free","Free","Free","Free","Free","Free","Free","Free","Free","Free","Free"}'
3	<i>MoverHomeTiles</i>	'{ { 2,1 }, { 3,1 }, { 4,1 }, { 2,2 } }'
4	<i>MoverTargetTiles</i>	'{ { 0,0 }, { 0,0 }, { 0,0 }, { 0,0 } }'
5	<i>MoverStationReservation</i>	'{ { 0,0 }, { 0,0 }, { 0,0 }, { 0,0 } }'
6	<i>MoverAvailabilityArray</i>	'{ "Idle", "Idle", "Idle", "Idle" }'
7	<i>ExtruderTiles</i>	'{ { 1,3 } }'
8	<i>ExtruderServingMoverAmount</i>	'{ 0 }'
9	<i>ImagerTiles</i>	'{ { 1,1 } }'
10	<i>ImagerServingMoverAmount</i>	'{ 0 }'
11	<i>ScannerTiles</i>	'{ { 3,3 } }'
12	<i>ScannerServingMoverAmount</i>	'{ 0 }'
13	<i>ApplicatorTile</i>	'{ { 4,3 } }'
14	<i>SeparatorTile</i>	'{ { 4,2 } }'
15	<i>TileRows</i>	3
16	<i>TileColumns</i>	4
17	<i>MoverTravelSpeed</i>	0.25 [m/s]
	Custom Output	Definition
21	<i>TileNumber</i>	parseNumber(substring(this.Name,5))
22	<i>TileCoordinatesXY</i>	[Tile].TileArray(parseNumber(substring(this.Name,5)))

The ***Tile*** submodel is presented in Figure 59. The submodel starts with the mover entering the input. The incoming mover is then assigned its target tile, which is read from the *MoverTargetTiles* array of the tile prototype (1). Subsequently, the tile status is declared as “Blocked by Mover...” (2). Based on the *TileDeltaX* and *TileDeltaY* attributes of the mover, which are calculated from the current coordinates of the mover and the targeted *Tile*, a decision is made on which *Tile* the mover must move to next in order to minimize the distance to the target. If several options are equally expedient, a random decision is made (3). In the event that this next movement causes the mover to reach its target, the status of the corresponding *Tile* is assigned as “DestinationReached” (4). Then it is checked whether the mover has reached a

station to carry out a process or reached its home position (25). In the first case, the mover leaves the *Tile* model via the exit output. In the second case, the *Tile* status is declared as “Home” (28) and a delay is waited for (26). After that, a check is made whether the *MoverTargetTile* has changed during this time (27). If this is not the case, the delay is waited again. If it is the case, the target is reassigned (1). If the *NextTile.Branch* (3) determines that the mover must move to an adjacent *Tile*, this is assigned in the attribute *NextTileToGoNumber* of the mover (5, 6, 7, 8). Subsequently, it is checked whether the *Tile* to which the mover should move next is blocked (9). If this is the case and the mover is less than two tiles away from the target, an attempt to resolve the blockage is initiated (11) with the option of redirecting (19) or, depending on the kind of blockage, a decision is made whether the mover should just wait (22). In this case, the *WaitCounter* is incremented (23) and the cycle time of the tile server is waited (24). Then the loop for determining the *NextTileToGoNumber* is run through again (3). If the *WaitCounter* reaches its limit, which indicates an unrealistically long waiting time that can potentially be caused by special deadlock situations, the mover is sent back to its home position (15).

In the event that a blockage is present (9), and the mover is more than two tiles away from the target, it is first assigned as waiting (12), and it is checked whether the mover is completely blocked and cannot move at all (13). If this is not the case, the blockage solver (11) is run through. If it is the case, the mover is delayed (14) and the wait counter is set to 0 (15). Then a random decision is made (20, 21) whether to continue waiting to get into the desired direction (22) or to move randomly in a different direction (19).

If there is no blockage (9) and the *NextTileToGo* has the status “Free”, it is checked whether this *Tile* is the *Tile* on which the mover was previously (10). This prevents movers from constantly driving back and forth if their desired *Tile* is occupied. If the mover is to move to the previous *Tile*, a configurable probability value (17) is used to decide whether the mover should be redirected (19) or allowed to leave the *Tile* via the previous *Tile* (16). If this is the case, the mover is declared as “leaving” and all parameters of the *Tile* are reset and released for new movers (18). Then, the directing branch (29) and the *NextTileToGoNumber* value are used to decide which exit the mover takes.

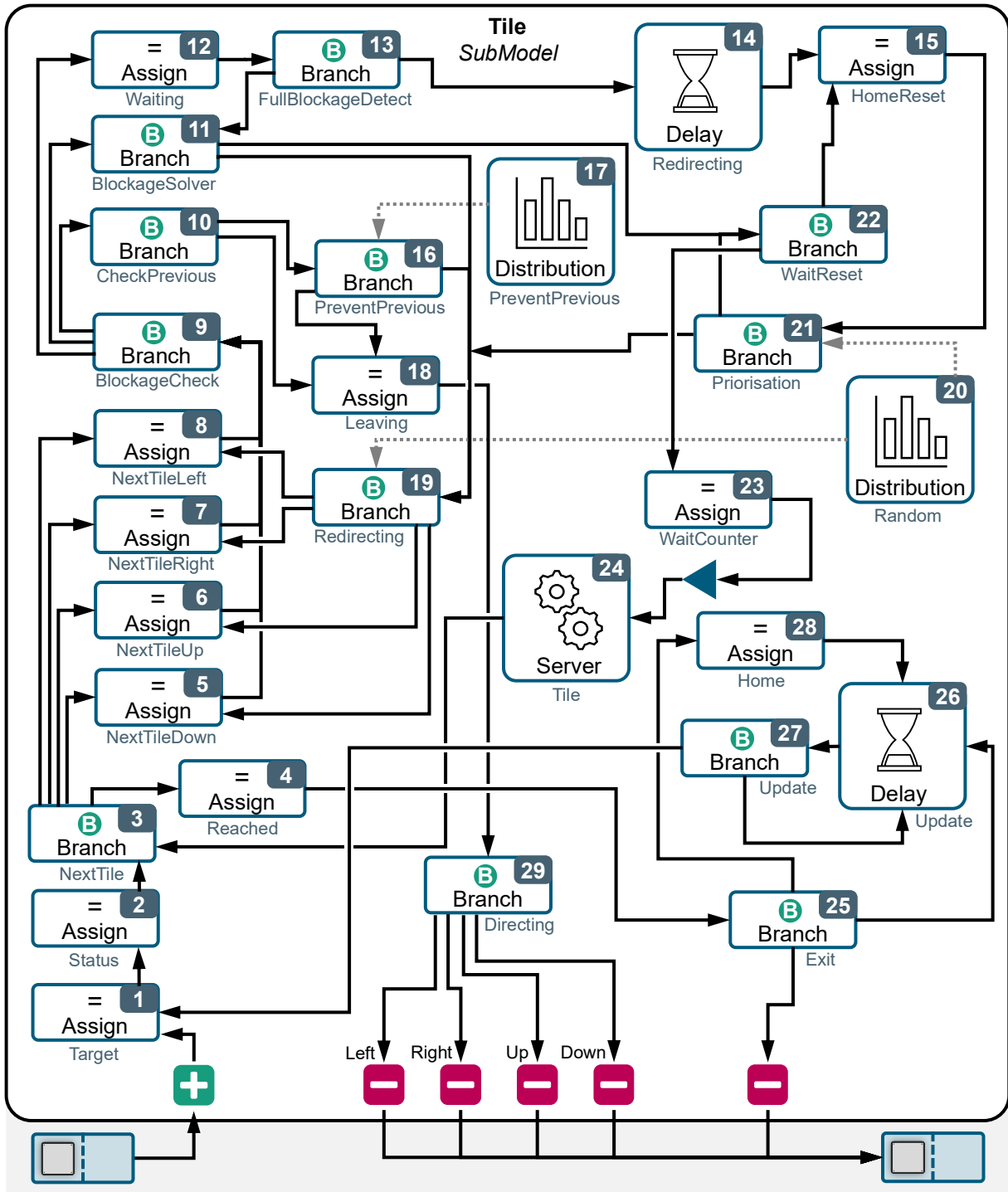


Figure 59: Simulation flow diagram of the *Tile* submodel

Table 35 in Annex A.10 provides an overview of the individual function blocks and a brief description of their respective function to supplement the figure of the submodel.

In summary, a modified form of a CBS algorithm (see Chapter 2.5) is implemented by this submodel structure and represents the MAPF logic explained in Chapter 3.6.3. The following simplifying conditions apply:

- Movers can only move to directly neighboring tiles and not diagonally. Unlike in the physical model, the trajectories are not optimized with regard to jerk minimization.

- The model acts decentralized on each tile and not superordinate for the entire planar drive system.
- The prediction horizon is limited to one tile. For each tile, the path planning predicts which state the next tile will assume and checks for conflicts until a solution is found.
- The first path identified as suitable is chosen and no global optimal solution is sought.

In addition, the decentralized path planning model was modified with regard to the following aspects in order to achieve better results for the use case:

- If a path is blocked, a decision is made depending on the distance to the destination and the duration of the blockage as to whether the mover should wait, or another path should be searched for.
- A mover always prefers not to move in the direction from which it has already come. However, if it is at a dead end, this is recognized, and the mover moves back.
- If there are equally valid possible paths, a random value is generated to prevent circular movements.
- If a mover is completely blocked or waiting times are exceeding a limit, the model can reset certain movers and send them back to the home position.

4.3.3 Printing Process for Scaffold Manufacturing

The **Extruder** submodel is presented in Figure 60. The submodel starts with the entry of a mover with an empty or partially printed substrate and the execution of the extruder step (1). The time spent on this process is determined by Equation 7 shown Chapter 4.1.1. Afterwards, the *LayerCount* attribute is incremented by 1 (2). A branch (3) and a configurable distribution (4) are used to decide whether or not the printed layer has an error (6). Accordingly, a new graphic is assigned for a defective scaffold (7) or for a partially printed scaffold (5). In this case, a new graphic is assigned in 10 % increments depending on the percentage of completion. Depending on the configurable QC interval, a decision is made whether a QC is to be carried out in the next step or whether the mover should move to its home position to cool down the printed layer (8). Accordingly, the mover's target tile is either written with the imager's coordinates (10) or with the home coordinates (9). When the homing process is initiated, the mover is duplicated (11) to send one duplicate out of the submodel and continue the process, while the other duplicate is delayed for the cool down period (12) to subsequently inform the other mover duplicate that the extruder is the target again and the next layer can be printed (13). The other duplicate is then deleted (14). Steps 11-14 ensure that if the mover is far away from the home position and would take longer to reach this position than the cool down requires, the homing process is ended prematurely to save processing time and avoid unnecessary paths.

Table 36 in Annex A.10 provides an overview of the individual function blocks and a brief description of their respective function to supplement the figure of the submodel.



4.3.4 Monitoring Process for Quality Assurance

The **Scanner** submodel is presented in Figure 61. It is a simple variation of a QC submodel (compare Chapter 4.1.2) and is used to simulate a one-time final inspection of a scaffold. The submodel starts with the entry of a mover with a finished scaffold that has the quality status “DefectFree” or “UndetectedDefect”. The duration of a scan process is simulated (1) and depending on a configurable error probability (3), a check is made to see if there is a defect (2), for example due to warping. The print job is then assigned either the status “passed” (4) or “failed” (5) accordingly. Finally, the *Separator* station is assigned as the new destination for the mover (6).

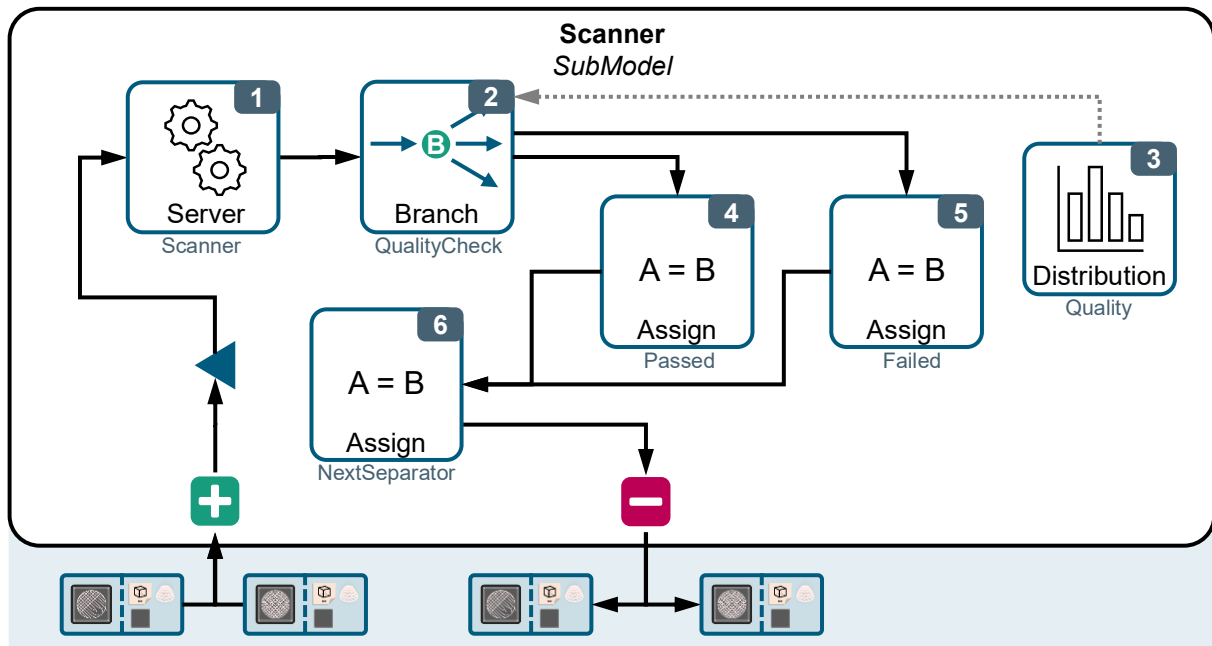


Figure 61: Simulation flow diagram of the *Scanner* submodel

Table 37 in Annex A.10 provides an overview of the individual function blocks and a brief description of their respective function to supplement the figure of the submodel.

The **Imager** submodel is presented in Figure 62. It is a variation of a QC submodel and is used to simulate a frequent inline inspection of a scaffold. The submodel is started with an entering mover with a partially printed scaffold. The duration of an imaging process is simulated (1) and depending on the *QCStatus* defect and defect-free scaffolds are sorted (2). For each branch, a test is simulated to see if a defect is detected (3, 5). For this, configurable probabilities are assigned for detecting a false negative (4) and a true negative (6) result. True and false defect detections are assigned (7, 10) and the separator station is assigned as the mover’s next target (8). For the scaffolds declared as “DefectFree”, the *RequiredLayers* and *PrintedLayers* attributes are compared (9). If they match, the *Scanner* is assigned as the next target for the final inspection (12). If additional layers need to be printed, the *Extruder* is the next target (11).

Table 38 in Annex A.10 provides an overview of the individual function blocks and a brief description of their respective function to supplement the figure of the submodel.

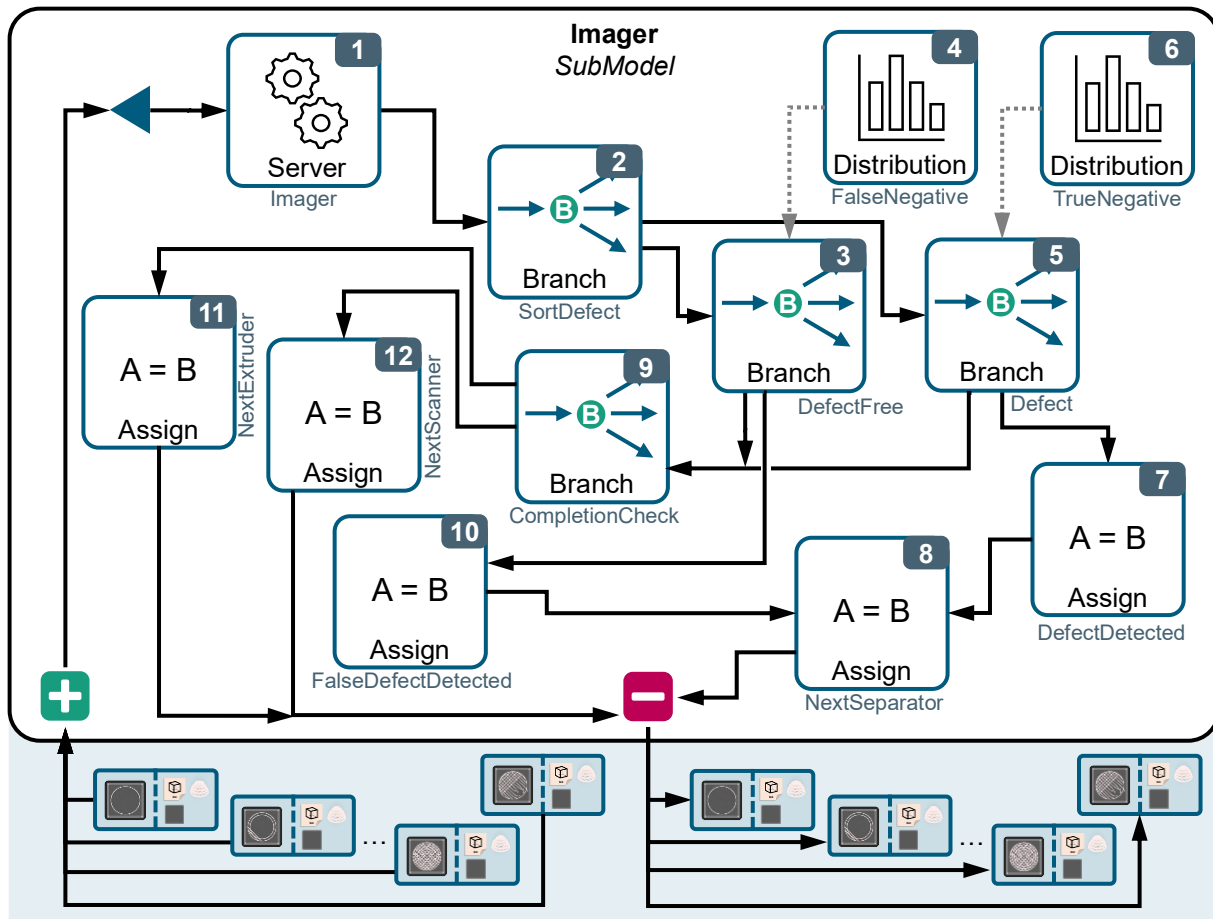


Figure 62: Simulation flow diagram of the *Imager* submodel

4.3.5 Detachment Process for Product Storage

The **Separator** submodel is presented in Figure 63. The submodel starts with the entry of a mover with a finished or broken scaffold. The Print Job entity is taken from the Mover container (1) and a check is made to see whether the job was successfully completed according to the *QualityStatus* (2). If this is the case, the information of the Print Job, including the completion time, is logged in an exportable report (3). The Job entity is then deleted (4). If the job was not completed successfully but was aborted beforehand, the restart of the job is initiated (5). To do this, the *MisPrints* attribute of the job is incremented, and the job leaves the submodel and is routed back to the *Computer* submodel, where the next mover takes over this Print Job. After the job has been removed from the mover container (1), the *Robot* resource is seized (6). The substrate including the scaffold is removed from the mover (7) and the mover's attributes are reset to the default values (9). The mover is then assigned a new graphic (9) and leaves the submodel. The scaffolds on the substrates also receive a corresponding new graphic without the mover (10). The movers are then sorted according to their *QualityStatus* (11) and a transport route is simulated with the robot, which either leads to the storage for finished scaffolds (15) or to a disposal container (12). The robot resource is then released again

(13, 16). A logger then saves all the process times that the corresponding scaffold has passed through in an exportable report (14, 17).

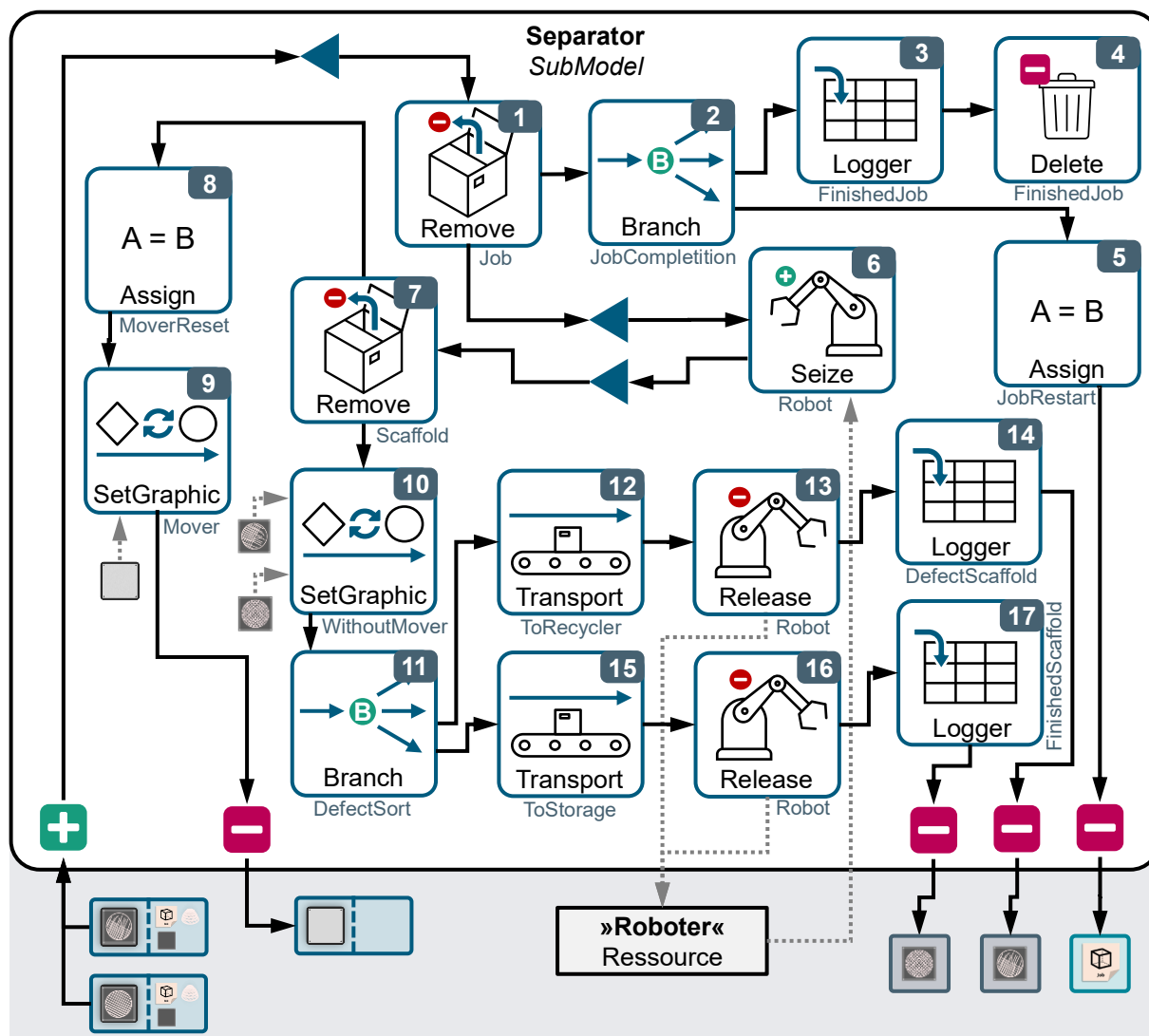


Figure 63: Simulation flow diagram of the *Separator* submodel

Table 39 in Annex A.10 provides an overview of the individual function blocks and a brief description of their respective function to supplement the figure of the submodel. Detailed information on the programming of the individual function blocks can be accessed via the information in Annex A.11.

4.3.6 Main Model Implementation

Figure 64 shows the interconnection of the individual submodels to form a complete simulation model. The interconnection of the individual *Tile* submodels of the *Planar Drive* system are not shown in this figure but are presented in Figure 58. The mover generation is implemented parallel to the submodel level. Four movers are integrated for the demonstrator use case, for each of which a home position is defined (H1 - H4). The Robot instance is connected to the modules that need to access it, in this case the *Applicator* and the *Separator*. Finally, a recirculation of failed jobs from the *Separator* to the *Computer* is implemented.

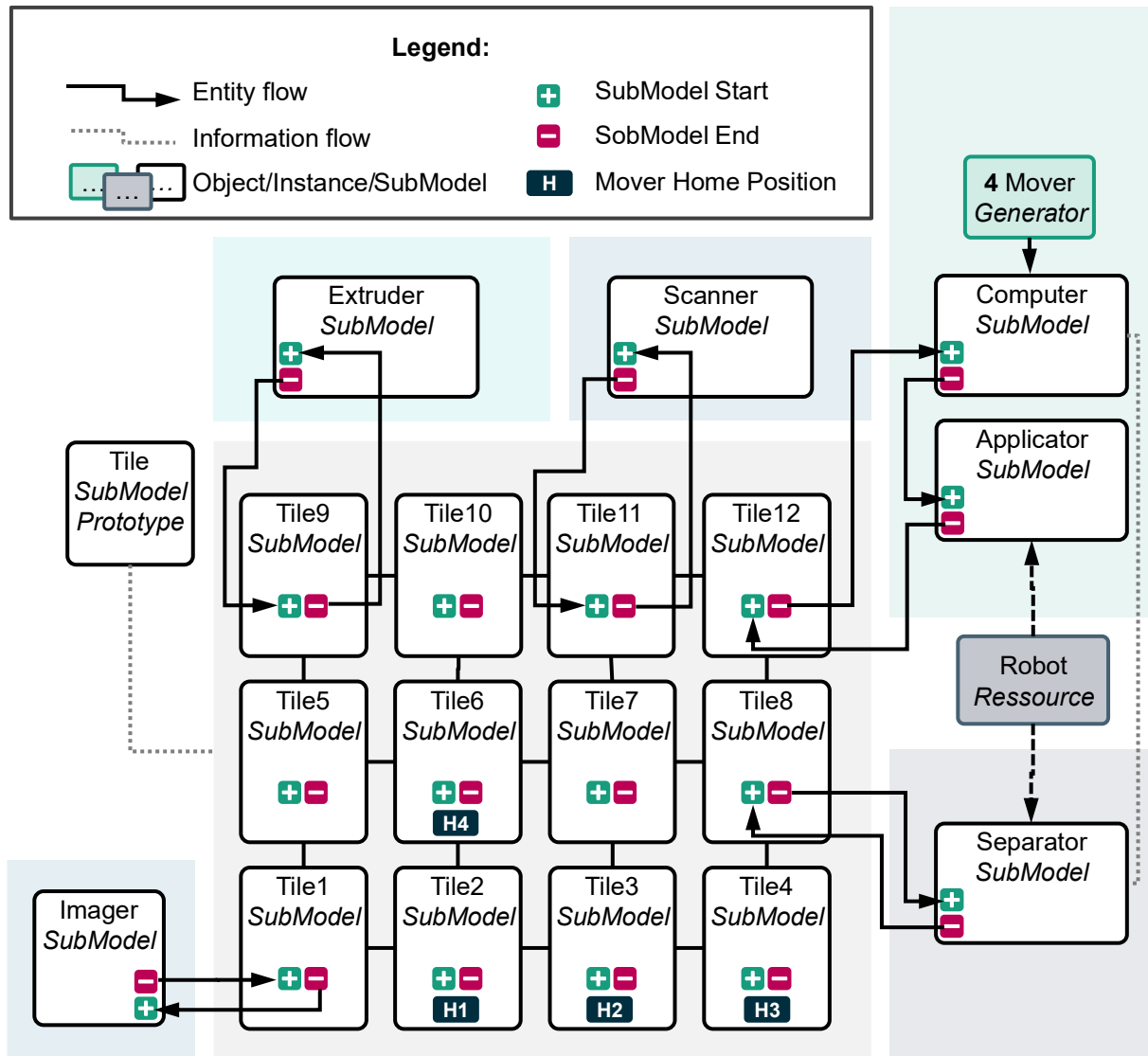


Figure 64: Simplified representation of the process flow diagram of the full simulation model for the demonstrator size production system

The JaamSim2024.07 DES environment is used to open the configuration files of the individual production models. The individual submodels with separate configuration files are accessed automatically. The programming of the individual submodels and the holistic production models are made accessible via the information in Annex A.11.

4.4 Parameterization

In this chapter, the implemented model is parameterized so validation tests can be carried out. For this purpose, the model is first parameterized in such a way that a representation of the physical demonstrator is realized. It is explained how the model is scaled on the parameter side in order to simulate different production scenarios. Finally, it is described which data is exported from the simulation, how it is processed and in what form it can be depicted and interpreted.

In addition to the boundary conditions defined in Chapter 4.1.1, which delimit the use-case-determining parameters, the following technical parameter assumptions in Table 15 are defined for the general use of the simulation model. These assumptions are kept consistent during the validation tests and for the comparison of different production scenarios. These assumptions of specific values are partially based on experimentally determined data or are assumed for the given application according to a literature review. These values are not subject to validation. The assumptions serve only the purpose of creating a specific use case and comparable scenarios for investigating the research questions.

Table 15: General parameters for setting up the submodels

Submodel	Parameter	Unit	Assumption Value
Extruder	CoolDownTime	s	20
Extruder	NozzleDiameter	mm	0,4
Extruder	ExtrusionRate	mm ³ /s	6,3
Extruder	PrintingTimeSurcharge	s	10
Extruder	ErrorRate	%	0,01
Imager	QCInterval	1	5
Imager	FalseNegativeDetection	%	0,1
Imager	TrueNegativeDetection	%	90
Imager	ImagingTime	s	10
Scanner	PassPropability	%	99,9
Scanner	ScanningTime	s	20
Robot	RoboticTransportTime	s	30
Applicator	ApplicationTime	s	3
Separator	SeparationTime	s	3

According to literature (compare Chapter 2.2.3), a cooling time of at least 5-10 seconds is recommended for printing PCL. This value is heavily dependent on whether an additional fan is installed on the extruder for component cooling. Within preliminary it was observed that the susceptibility of warping defects can be reduced with extended cool-down (Bouzaglou et al.,

2023). Accordingly, a cool-down time of 20 seconds was assumed. The same duration is also set for the physical demonstrator.

The assumed nozzle diameter is the same as that of the extruder on the demonstrator. The extrusion rate was estimated on the basis of preliminary tests with the physical extruder. For this purpose, a volume of PCL was extruded with a constant motor speed for a period of 10 seconds. The extruded volumes were weighed. Five test replications were conducted. Taking the density of the PCL ($1,21 \text{ g} \cdot \text{cm}^{-3}$) into account, the mean extrusion rate was $6,3 \text{ mm}^3/\text{s}$ with a standard deviation of $0,43 \text{ mm}^3/\text{s}$. A surcharge time is added for the printing time, which is approximated in Chapter 4.1.1. This simulates the time required for the Z-axis movement before and after printing a layer. The value varies individually for each process; for simplification, a fixed value of 10 seconds is assumed.

Based on practical observations during printing tests a general error rate of 10 % was assumed for the production of a scaffold. This assumption is highly dependent on the definition of the tolerance range of the quality attributes of the product. Since this work only examines the simulation ability, and no tolerance interval can be defined for the fictitious products, the probabilities were chosen so that a defect rate of about 10 % is achieved for all production scenarios (see Chapters 5.2 to 5.4). The value for the extruder's error rate, which indicates the probability of a single printed layer being defective, is set to 0,01 %. The imaging defect detection probabilities for the occurrence of false and true negative detections are assumed to be 0,1 % and 90 %. The *Scanner* pass probability represents the probability that a defect free scaffold passes the final inspection is set to 99,9 %. The processing times for the *Scanner*, *Imager*, *Robot*, *Applicator* and *Separator* are approximated based on qualitative observations on the demonstration system.

Model Set-up on Demonstrator Scale

Figure 65 shows the implemented JaamSim model of the demonstrator on the corresponding scale. In contrast to the physical system, peripheral system segments such as the robot and the storages are added to the simulation model in order to close the automation loop. The model and the demonstrator consist of twelve tiles, one extruder, one scanner, one imager and four movers. Numerous process data can be exported from the simulation model, which are explained in more detail in Chapter 4.4.

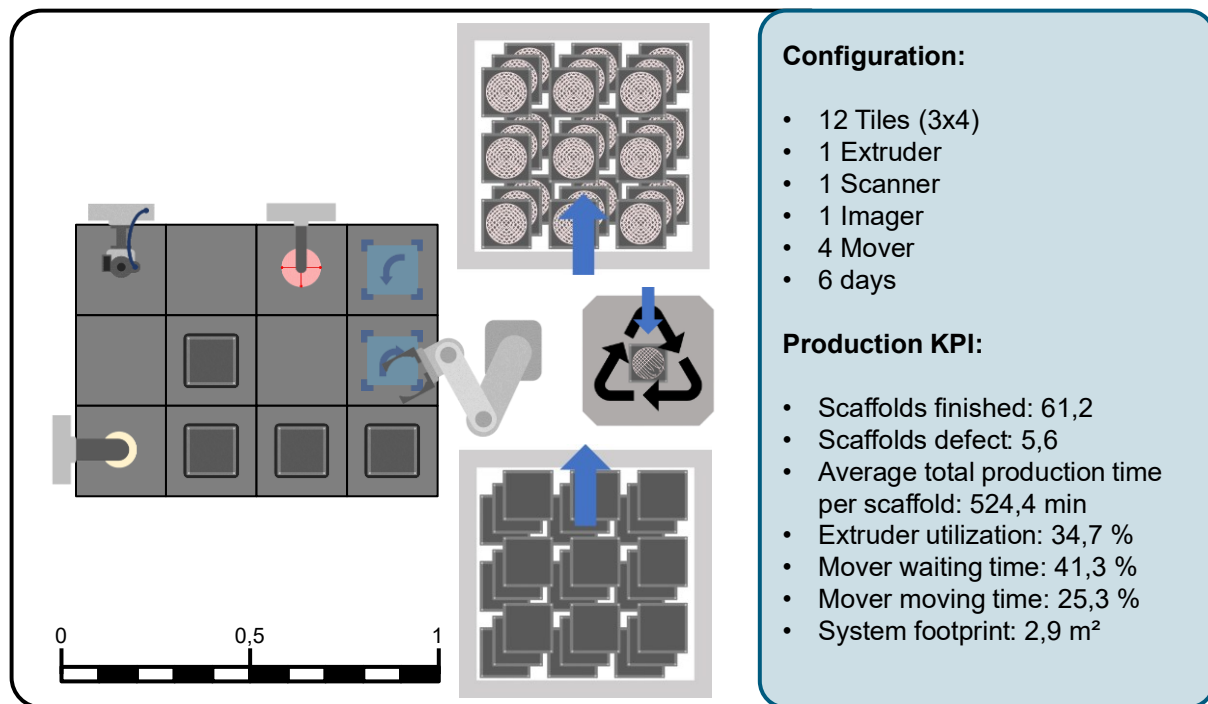


Figure 65: Overview of the model for the demonstration system implemented in JaamSim, including the main configurations and selected production KPI

Important KPIs for production are, on the one hand, the number of scaffolds completed within the six-day production period, referred to as production throughput. The number of defective scaffolds is consistently around 10 %, which is predetermined by the configuration of the extruder and the QC and therefore cannot be optimized by the production layout. However, the value is shown for overview purposes. Another KPI is the average production time required for one scaffold, known as the Actual Order Execution Time (AOET), compare 2.6. This is generally different for each individual scaffold but is significantly influenced by waiting times at the stations. The extruder utilization indicates what percentage of its available time the extruder is actually working, also referred to as the Overall Equipment Effectiveness index (OEE). This value is strongly influenced by the layout. Since there is a mover surplus compared to the extruders in this scenario, this extruder should theoretically operate at maximum capacity.

However, since the extruder is located in a corner and the movers wait in front of the extruder, blocking the finished mover, a more complex path planning maneuver must be carried out before each mover position change at the extruder is finished. This maneuver results in the extruder being unused for several seconds. The mover waiting time can provide information about how well the ratio between movers and stations is configured and should be minimized. Depending on the simulation objective, analyzing the OEE of the other station can be helpful. The mover moving time can provide information about how favorably the home positions of the movers have been chosen and how efficiently the routes are driven. These times should also be kept as short as possible.

Due to the integration of the system in a cost-intensive cleanroom environment, the footprint of the machine is added as an KPI and is desired to be minimized. The following equation is used to approximate the system's footprint:

$$FP = (T + E + S + I) \cdot T_{Area} + P_{Area} \quad (8)$$

FP: System Footprint

T: Number of Tiles

E: Number of Extruder

S: Number of Scanner

I: Number of Imager

P_{Area}: Area of peripheral systems (= 2 m²)

T_{Area}: Area of one Tile (= 0,24 m · 0,24 m)

Table 16 shows in a condensed form the attributes of the model that need to be configured manually depending on the production scenario. On the one hand, the coordinates of the individual tiles must be entered in the *TileArray*. On the other hand, the home positions of the movers are stored in the *MoverHomeTiles* array. The other attributes each indicate the positions of the respective stations. If a non-rectangular planar drive surface is implemented, a rectangular surface must still be created, with the corresponding non-existing tiles in the *TileStatusArray* being declared as an “Obstacle”.

Table 16: Attributes of the planar drive model that have to be configured manually for the demonstrator scenario

Line	Planar Drive Tile Attributes	Definition
1	TileArray	'{ { 1,1 }, { 2,1 }, { 3,1 }, { 4,1 }, { 1,2 }, { 2,2 }, { 3,2 }, { 4,2 }, { 1,3 }, { 2,3 }, { 3,3 }, { 4,3 } }'
2	MoverHomeTiles	'{ { 2,1 }, { 3,1 }, { 4,1 }, { 2,2 } }'
3	ExtruderTiles	'{ { 1,3 } }'
4	ImagerTiles	'{ { 1,1 } }'
5	ScannerTiles	'{ { 3,3 } }'
6	ApplicatorTile	'{ { 4,3 } }'
7	SeparatorTile	'{ { 4,2 } }'

Model Set-up on Production Scale

As elaborated in Chapter 3, the production infrastructure was developed to allow scalability of production capacity. Analogous to Figure 65, Figure 66 shows an exemplary scenario of a scaled production for >1000 individualized reference scaffolds per week.

The manual configuration of the model is carried out in the same way as described for Table 16. The specific attributes of the scaled model are listed in Annex A.11 in Table 40.

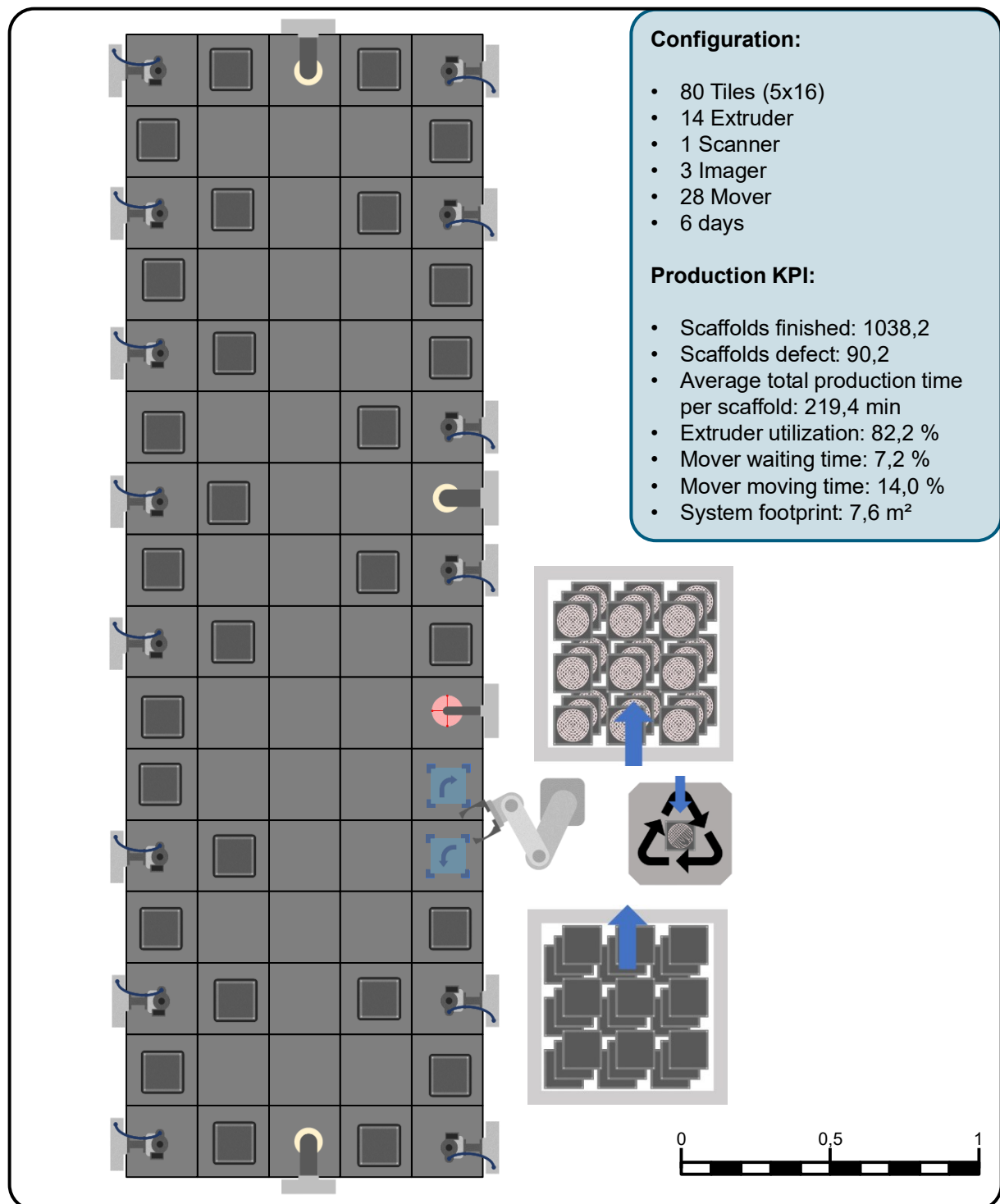


Figure 66: Overview of the model for an exemplary large-scale production implemented in JaamSim, including the main configurations and selected production KPI

Data Output Processing

The logging function in JaamSim provides the option to register states for individual simulation entities and to record the corresponding times an entity spends in this state. In addition, specific attributes can be read and summarized into averages or sums.

Table 17 shows an output report with all logged data. The number of finished and defective scaffolds are logged as total values. The number of movers and stations used is read directly from the configuration. The average total production time is the average total time that a print job needs for completion. The other average times listed add up from the times that a mover with a print job spends in the different states. This then results in percentage values such as the Average Mover Waiting Time and the Average Mover Moving Time.

Table 17: Exemplary output report of a simulation run with 5 replicates for the scaled production layout from Figure 66. KPIs are marked in bold.

Parameter	Unit	Value					Average
Replication		1	2	3	4	5	
Amount Finished Impants		1061	1032	1028	1031	1039	1038,2
Amount Defect Implants		85	102	97	78	89	90,2
Amount Active Movers		28	28	28	28	28	28
Amount Active Extruder		14	14	14	14	14	14
Amount Active Imager		3	3	3	3	3	3
Amount Active Scanner		1	1	1	1	1	1
Average Total Production Time	min	216,5	220,2	220,3	221,1	218,8	219,4
Average "Printing" Time	min	86,8	88,5	88,5	88,9	88,0	88,1
Average "Scanning" Time	min	0,3	0,3	0,3	0,3	0,3	0,3
Average "Imaging" Time	min	9,1	9,2	9,2	9,2	9,1	9,2
Average "Moving" Time	min	29,5	31,0	31,1	31,4	30,5	30,7
Average "WaitForExtruder" Time	min	8,2	8,3	8,3	8,3	8,1	8,2
Average "WaitForScanner" Time	min	0,4	0,4	0,5	0,5	0,4	0,5
Average "WaitForImager" Time	min	6,7	6,9	7,0	6,9	6,8	6,9
Average "WaitForRobot" Time	min	0,3	0,3	0,3	0,3	0,3	0,3
Average "RoboticTransport" Time	min	0,2	0,2	0,2	0,2	0,2	0,2
Layer Cool Down Time	min	0,3	0,3	0,3	0,3	0,3	0,3
Average Total CoolDown Time	min	75,0	75,0	75,0	75,0	75,0	75
Total Simulation Time	d	6,0	6,0	6,0	6,0	6,0	6
Total Printing Time	d	4,93	4,98	4,94	4,89	4,92	4,9
Extruder Utilization Percentage	%	82,2	83,0	82,3	81,5	82,1	82,2
Average Mover Waiting Time	%	7,2	7,2	7,3	7,3	7,2	7,2
Average Mover Moving Time	%	13,6	14,1	14,1	14,2	13,9	14,0

These automatically generated reports are used to examine different hypotheses by comparing different scenarios under the same boundary conditions. The generation of all simulation data is carried out as part of the validation and is presented in Chapters 5.2, 5.3 and 5.4.

4.5 Summary of Interim Results

In this chapter, based on the production concept resulting from Chapter 3, a digital model for the event-discrete simulation of production scenarios in the context of extrusion additive manufacturing personalized medical scaffolds was systematically developed.

Methodically, the following approach based on the guideline VDI 3633:2018 was taken:

- Definition of the modeling framework, including modeling and simulation objectives and the description of the processes to be modeled
- Formal modeling of the material and information flows and conceptual design of the model architecture
- Implementation of submodels and set up of the full simulation model
- Parameterization of the simulation models for further validation and verification

Technically, the following results were achieved:

- A model architecture was developed that enables a modular digital replication of a production environment in which individual products can be manufactured in a scalable manner using EAM.
- Due to the predefined production use case of personalized medical scaffolds, the requirements for quality assurance are particularly high. Therefore, the model was designed that a variety of different QC systems can be integrated in a configurable way to adequately monitor the product-specific quality requirements.
- With the planar drive system-based production concept, which is the main subject of the modeling, a decoupled, flexible production approach was pursued and was fully digitally replicated.
- For the use of the developed model for scaling and optimization planning of production infrastructures, a data output was implemented to collect and compare production KPIs for different scenarios.

Figure 67 illustrates the resulting digital production model as well as its capabilities and relevance for further validation. First, the model is given inputs regarding the simulation conditions. This concerns the simulation time and the number of replications. At the process level, a large number of parameters can be defined, which, for example, affect the planar drive or extruders. The individual production scenarios are activated via a system configuration. Therefore, the number and positioning of the individual devices must be set. In addition, disruptive factors such as error rates or downtimes can be configured to examine the resilience of a production or to adopt these values to a real system. Along with this, the QC systems can be configured, for example by defining their sensitivity or specificity. On the product side, the degree of customization and tolerance ranges for its quality attributes can be defined in order to ultimately configure a production scenario holistically. The outputs that can be generated from the respective discrete-event simulation of a production scenario primarily address product throughput. In addition, all process times are recorded to identify bottlenecks or logistical problems.

Supplementing this, further data could be connected to allows techno-economic analyses. This would include, for example, material, investment and operating costs, which then could be analyzed for different production scenarios. Sustainability assessments can also be realized by comparing power consumption by simulating different production scenarios. This is discussed in more detail in the outlook in Chapter 7.

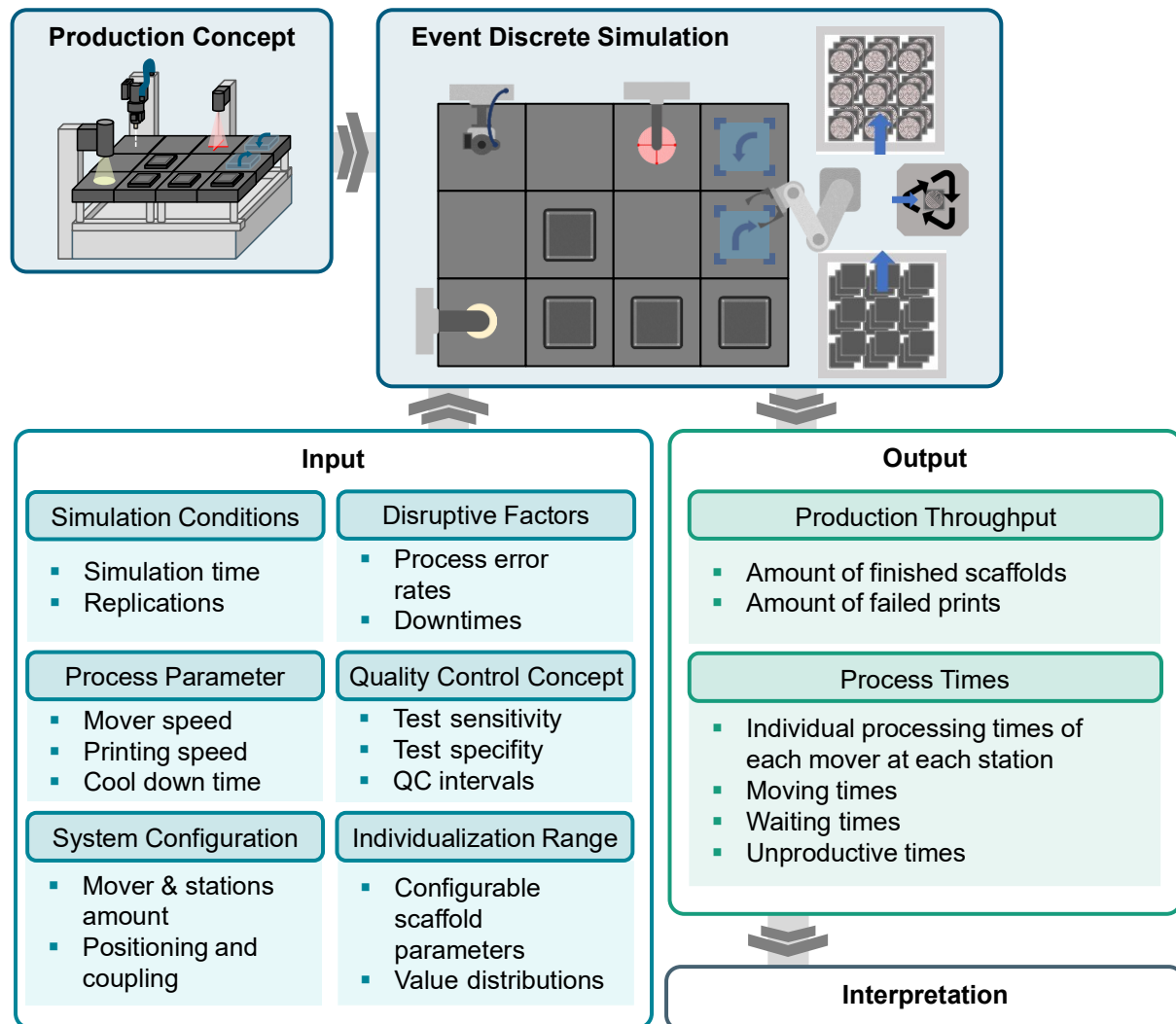


Figure 67: Overview of the inputs used to configure the developed simulation model and the outputs that can be obtained from the simulation

The results, thus provide an answer to the sub research question **SRQ3 “How can an automated scaffold production infrastructure be digitally modeled?”**. For the sub research question **SRQ4 “Can the digital production model be used for production planning regarding scalability and optimization?”**, the developed model provides the necessary tool to answer the question, but the verification to affirm this question is provided by the simulation results, which are presented in the context of the testing and validation in Chapters 5.2 and 5.3. This chapter together with Chapter 3, complete the steps (C), (D) and (E) of the research process according to Ulrich, compare Figure 5 (Ulrich and Hill, 1976), about method specification, investigations and model development. In the following, step (F) about “Testing the rules and models in the application context” is introduced.

5 Testing and Validation

This chapter concludes the development process of the production system and validates the answered research questions. In the context of production technology, the glossary of the standard DIN EN ISO 9001:2015 defines the term validation as “the confirmation by provision of objective evidence that the requirements for a specific intended use or application have been fulfilled” (DIN Deutsches Institut für Normung e.V., 2015). The Institute of Electrical and Electronics Engineers (IEEE) and its Standard Glossary for Software Engineering Terminology defines validation as „the process of evaluating a system or component during or at the end of the development process to determine whether it satisfied specified requirements“ (IEEE, 1990).

Accordingly, measures were derived to answer the research questions in order to objectively examine whether the defined requirements are satisfied. These measures are listed in Figure 68 and described hereafter. The validation of the production infrastructure and the answering of the research questions are based on three pillars:

1. Literature Review

Based on a systematic literature review, all regulatory requirements from official legislations are determined, as shown in Chapter 2.3. On the other hand, based on the state of the art, relevant process parameters and quality attributes are determined, compare Chapter 2.2.3. Considering the use case specified, the CPPs and CQAs are derived, as can be seen in Chapter 3.1.2. Thus, the SRQ1 was answered in Chapter 3.8.

2. Physical Demonstrator

The demonstrator of the conceptualized production infrastructure from Chapter 3 is used to validate the technical innovations on which the concept is based. To this end, concept proofing experiments are carried out as part of the validation. These include the verification of planar-drive-based EAM, integration of QC measures and dynamic interconnected multi-agent EAM. The results of these experiments can be used to answer SRQ2.

3. Digital Production Model

In Chapter 4, a digital representation was developed for the conceptualized production infrastructure, which can be used to simulate different production scenarios and layouts. The validity of the realistic representation of this model is examined by conducting a comparative study with the physical demonstrator. This provides the answer to SRQ3. With this proof of concept, the digital model is then used to plan the production infrastructure in different layouts for increased throughput scales. Investigating whether the model can be used to optimize the production infrastructure with regard to technical performance indicators, provides the data to answer SRQ4.

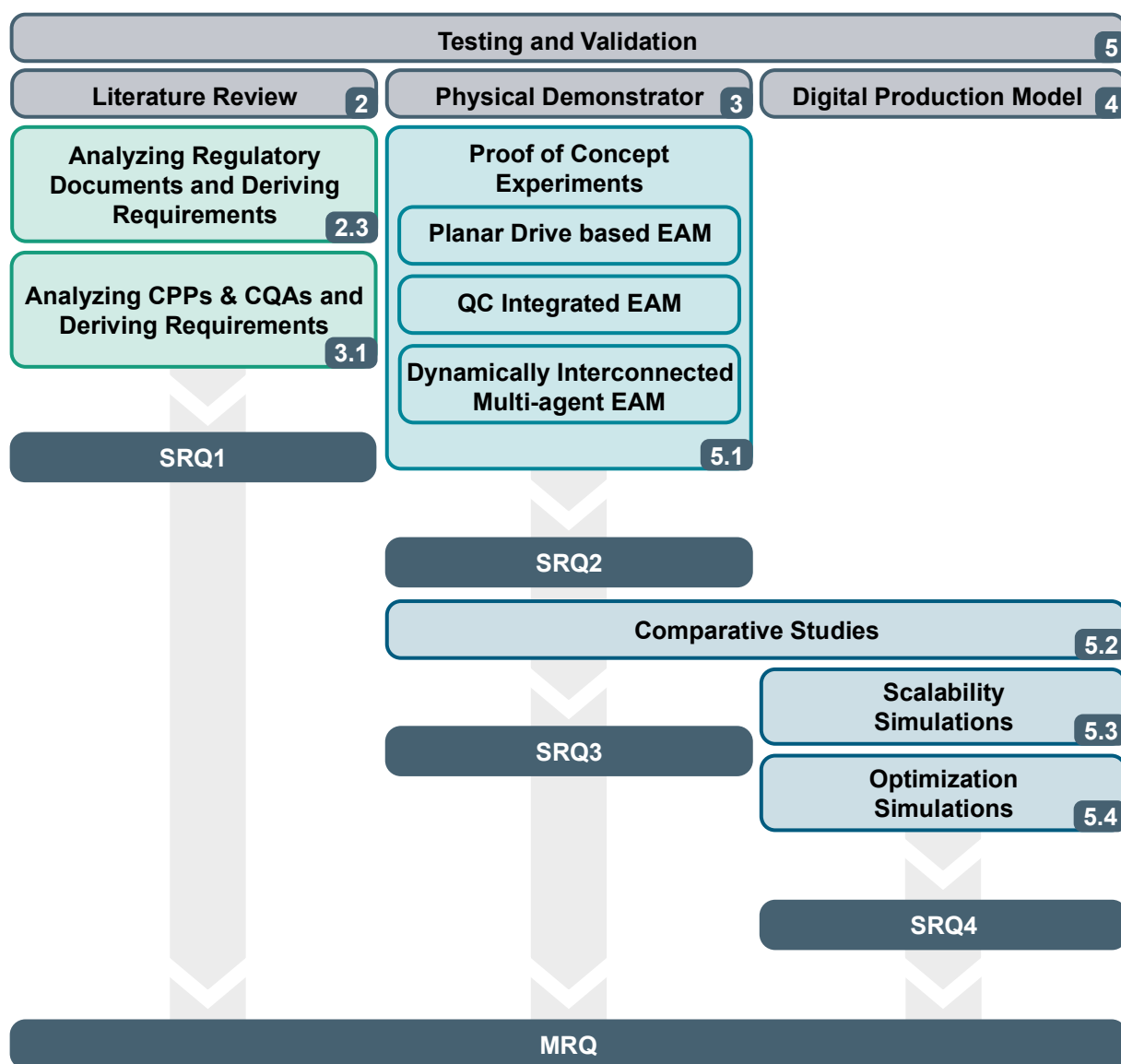


Figure 68: Testing and validation structure with the individual measures, the associated research questions and corresponding numbering with the chapters of this thesis

After all sub research questions have been answered by the validation experiments and simulations, as shown in Figure 68, the MRQ is answered in the validation conclusion in Chapter 5.5. Critical aspects and limitations of these investigations are discussed in Chapter 6.

5.1 Proof of Concept Experiments on Demonstration System

In this chapter, the tests are carried out to verify the general technical suitability of the developed production infrastructure for manufacturing personalized scaffolds. For this purpose, the experiments are divided into three clusters, see Figure 33.

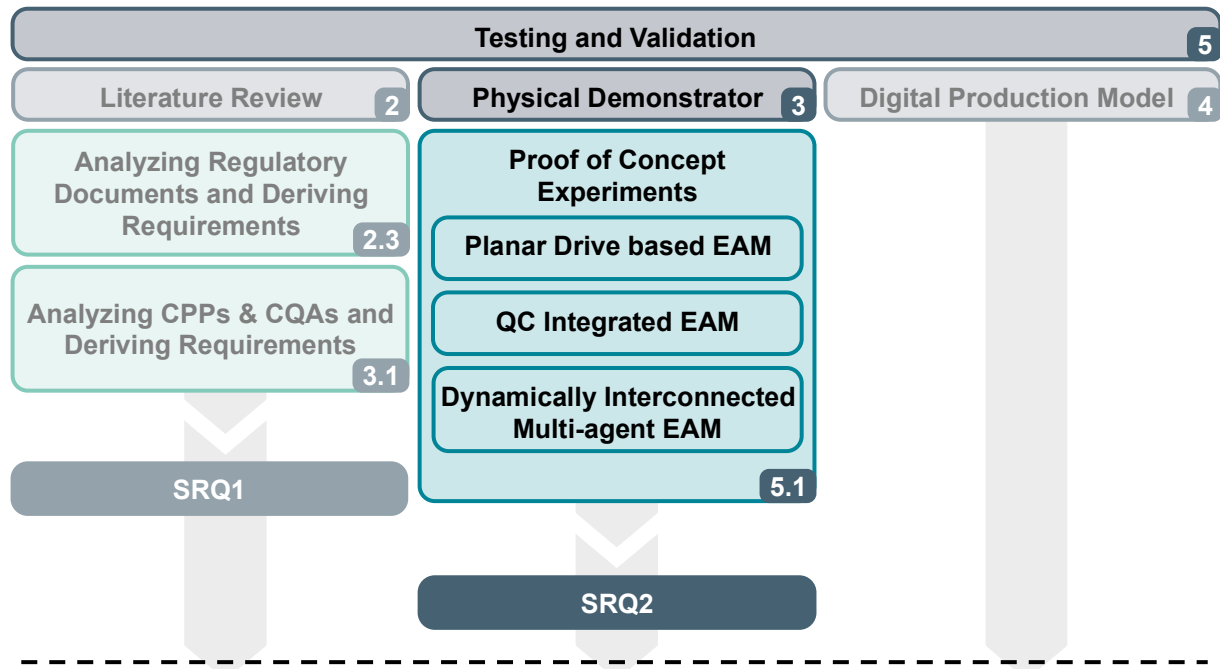


Figure 69: Segment of the testing and validation structure with focus on the concept proving experiments with the physical demonstrator.

Firstly, the ability to reproducibly print scaffolds using a planar drive-based EAM machine is investigated. Therefore, ten scaffolds are printed with the PEAM and for reference three scaffolds are printed with an established conventional printer. The scaffolds will be measured, photographed and characterized with regard to their quality attributes.

Secondly, the integrability of QC into the process is examined. To do this, an imaging station is integrated into the printing process, whereby a scaffold with 100 layers is printed, with each ten layers being imaged. The process times and the recorded images are documented.

Thirdly, the approach of dynamically interconnected multi-agent EAM is examined. Therefore, printing experiments with two, three and four movers are carried out, which produce scaffolds in parallel on one extruder. The motion sequences are observed and graphically displayed. All process times are recorded and compared.

The individual experiments are conducted and presented in the structure shown in Figure 70.

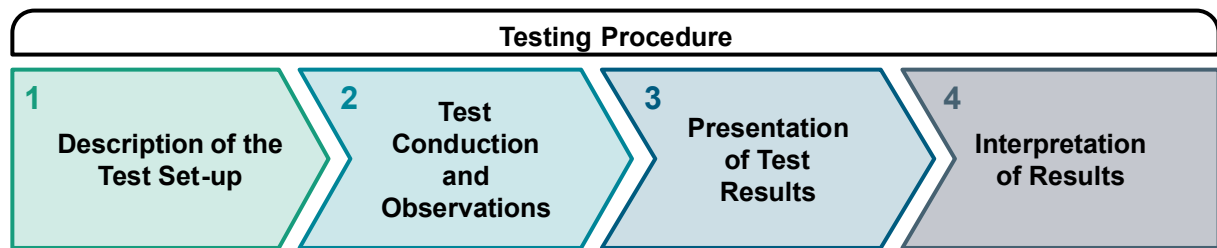


Figure 70: Structural procedure for conducting the experiments

5.1.1 Planar Drive based Extrusion Additive Manufacturing

The experiments on the proof of principle (PoP) of PEAM's suitability for 3D printing are presented. The test set-up is explained, the test procedure is described, and the data obtained is presented and finally interpreted.

Description of the Test Set-up

The DIAMS demonstration system resulting from Chapter 3.7 is the subject of the PoP and is used for the experiments. The hardware used is explained in detail in Chapter 3.4.4. Figure 71 shows the overall structure, as well as the extruder, including the mover and print bed.

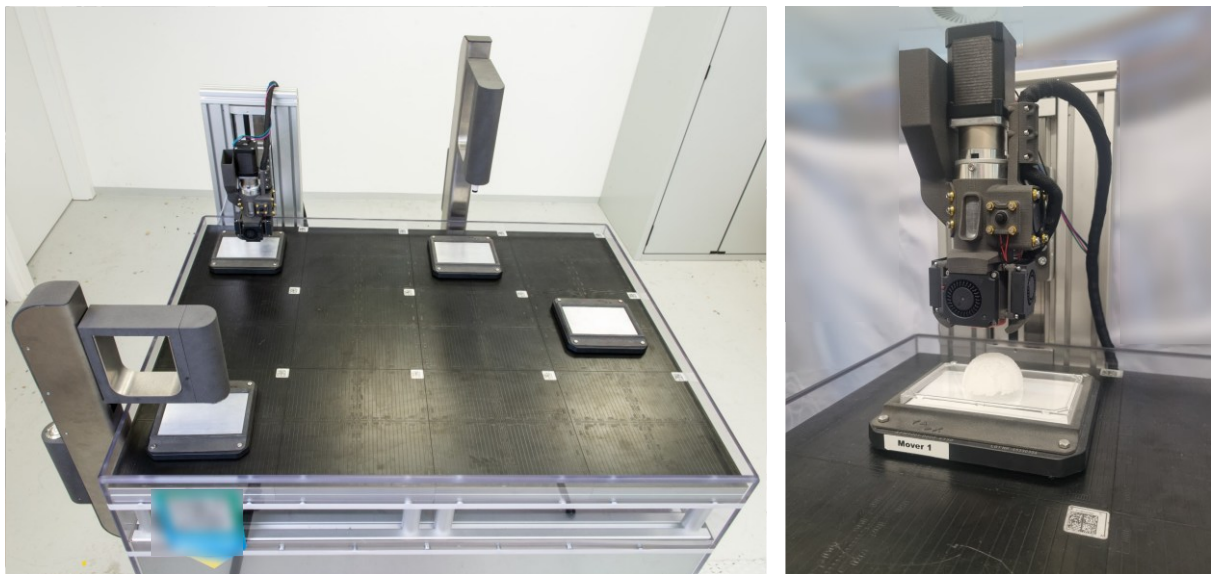


Figure 71: Test setup on the DIAMS demonstrator, as well as the extruder and mover print bed

Differing from the defined test scaffold used in the modeling in Chapter 4.3, the following experiments do not use a half-sphere as the basic geometry, but a cuboid with the outer dimensions of 50 mm * 50 mm * 20 mm and a layer height of 200 μ m. This test scaffold geometry was chosen to enable easier and more reproducible measurement of the quality parameters of the scaffolds, such as outer dimensions. Figure 72 schematically shows all dimensions of the test scaffold and a CAD rendering of the scaffold body.

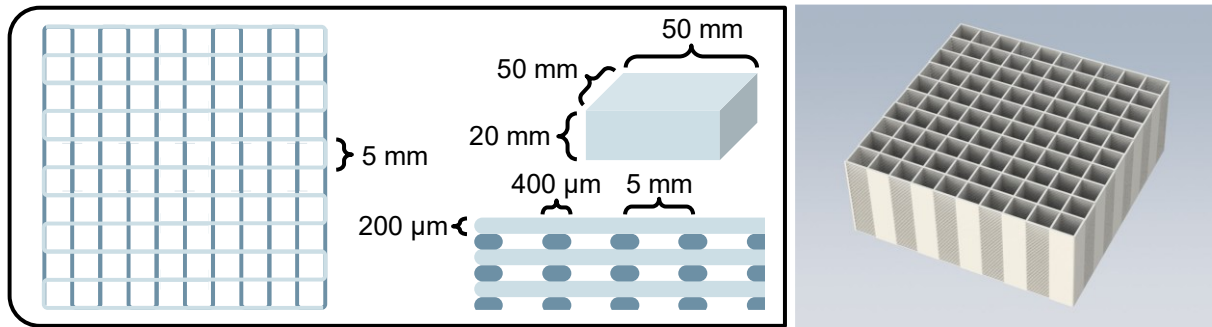


Figure 72: Schematic illustration of cuboid test scaffold

The Princore Extruder was equipped with a 400 μm nozzle, the temperature of which was set to 130 °C and a deposition speed of 150 m/s was set by adjusting the mover speed of the planar drive system while printing. For these experiments, all but one mover was deactivated. The height of levitation of this mover was set to 2 m. A polystyrene plate was used as a substrate. The leveling of the Z-axis was done manually.

Test Conduction and Observations

The extruder was loaded with PCL granules and heated. As soon as the nozzle and the inner extruder sensor had reached a temperature of 130 °C, which took about 25 minutes, extrusion was started. During the initial extrusion with new material, the extruder screw was operated until a consistent thread of material was extruded. Then the extrusion was stopped and the extruded material, which was collected manually, was disposed of. Then the 3D printing program was started. The mover moved centrally under the extruder and the Z-axis moved to the printing bed. The G-Code movement of the mover and the material extrusion of the extruder were started simultaneously. The first layer was printed and then a cool-down time of 20 seconds was waited. After that, the Z-axis, together with the extruder, moved up by the corresponding layer height and printed the next layer. This was continued until all layers were printed.

A total of ten scaffolds were printed and documented using the PEAM with the same settings. In addition, three further scaffolds were printed with a conventional EAM printer based on a gantry system as a comparative reference. The Anycubic Kobra 2 3D printer was used. As printing material, also PCL was used but in filament spool form and not as granules.

During the printing process, it was noticed that there were fluctuations in the mover movements at the levitation height, explained as wobbling in 3.6.1. In addition, intermittent material drop-outs from the extruder nozzle occurred. Stringing was observed during most of the tests.

The fabricated scaffolds were separated from the substrate and the outer dimensions as well as the weight were measured. In addition, the scaffold was photographed to assess the quality attributes. The scaffolds are evaluated according to the following criteria:

- Stringing
- Displacement
- Over- or under-extrusion

- Outer shape deformation
- Impurities

Stringing is evaluated by analyzing the recorded top view images with regard to the areal occurrence of stringing. This involves checking the percentage of pores in which strings can be identified. Compare Picture A in Figure 73. When assessing displacement, a binary evaluation is made to determine whether at least one filament has been notably misplaced. For this identification, the same images are used (B). Over- and under-extrusion is assessed in two ways. Firstly, the scaffold is weighed and the deviation from the standard value is checked to determine whether too much or too little material was extruded overall. In addition, the image recordings are examined and checked for local over- or under-extrusions. This is done using a qualitative binary evaluation using the top view images (C).

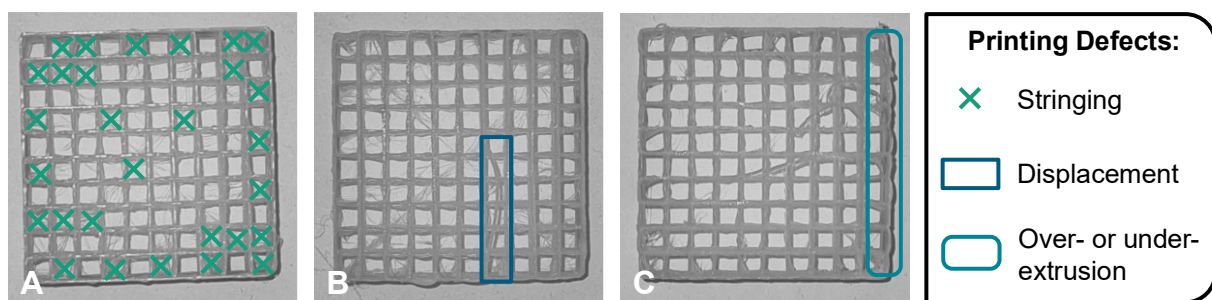


Figure 73: Evaluation of printing defects in scaffolds

Outer shape deformation is assessed, on the one hand, by measuring the outer dimensions of the scaffold and comparing them with the target value and, on the other hand, by visually inspecting whether a significant warping effect has occurred. A deformation of more than 2 mm (10 % of the scaffold height) is considered significant. Impurities are also visually inspected. The presence of a single foreign body in the scaffold leads to the classification as impure.

Presentation of Test Results

In the following, the scaffolds manufactured using PEAM are shown in Figure 75 and the reference scaffolds from a conventional EAM system are shown in Figure 74.

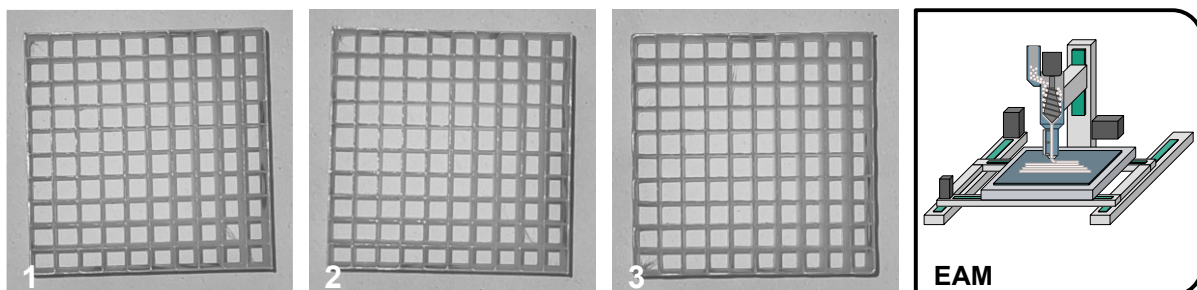


Figure 74: Images of the test scaffolds produced using EAM as a reference

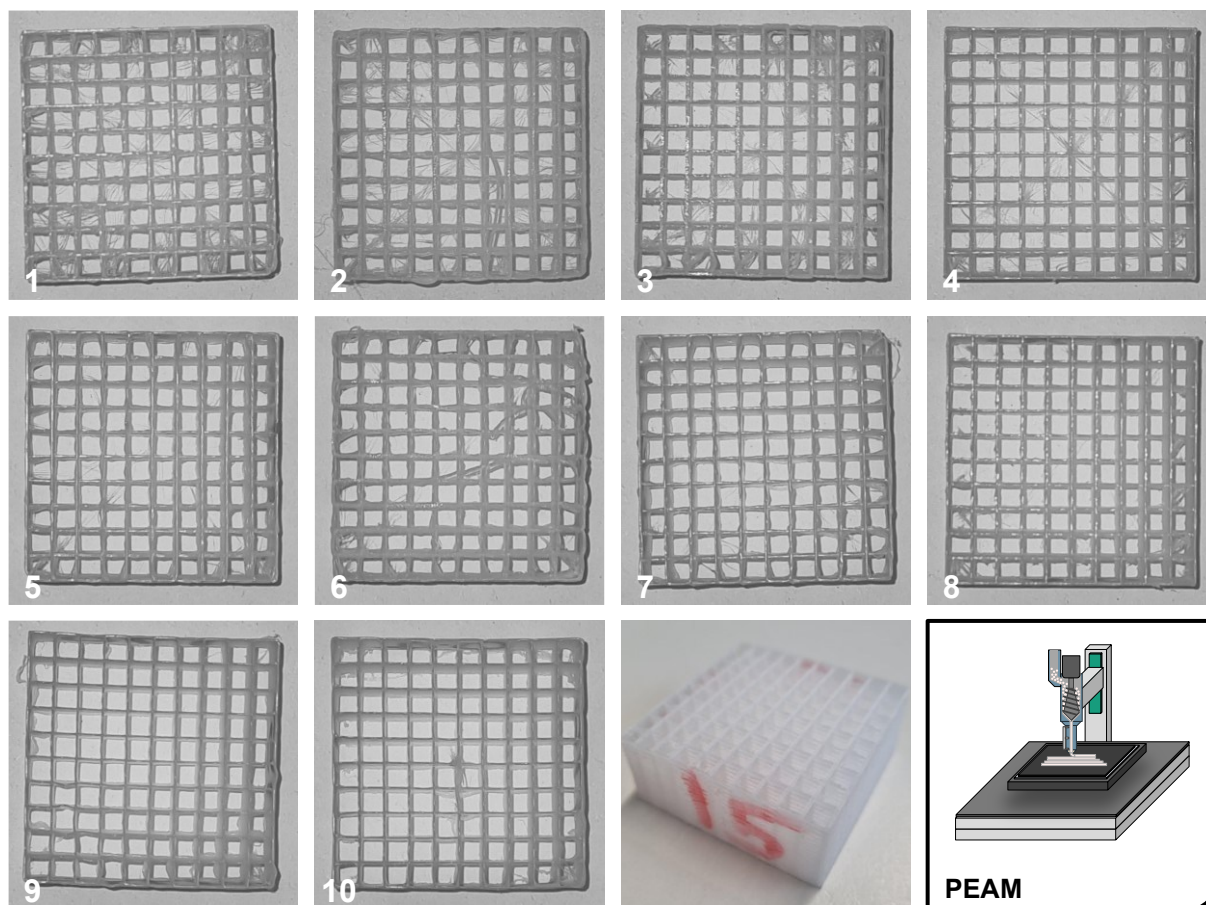


Figure 75: Images of the test scaffolds produced using PEAM

During the experiments and by reviewing the images, it was observed that the stringing effect decreased over time. Generally, when looking at the images, there are some noticeable differences in quality. The data obtained from the images and the measurement of the scaffolds are documented in Table 18. It can be seen that the conventional EAM system achieves comparable values to the PEAM system in terms of the side lengths of the printed scaffolds, with the EAM system showing higher reproducibility with a standard deviation of 0,2 mm compared to 0,3 mm. Regarding height, PEAM generally achieves lower values than EAM. The weight of the scaffolds produced using EAM and PEAM also differs by generally 1 g. Furthermore, it was observed that stringing defects occurred significantly more frequently with PEAM and that there were occasional cases of displacement and over-extrusion.

Table 18: Measured attributes of scaffolds produced using PEAM and EAM

Scaffold	Length 1	Length 2	Hight	Weight	Stringing	Dis- place- ment	Over-/ Under- Extrusion	Warping	Impurity
	[mm]	[mm]	[mm]	[g]	[%]	[Y/N]	[Y/N]	[Y/N]	[Y/N]
PEAM	1	50,7	50,2	19,6	8,31	60	N	N	N
	2	50,2	50,5	19,6	8,27	50	Y	Y	N
	3	49,7	50,5	19,5	8,11	40	N	Y	N
	4	50,1	50,7	19,6	8,23	40	N	N	N
	5	49,6	50,4	19,7	8,28	20	N	N	N
	6	50,5	49,9	19,5	8,16	10	Y	Y	N
	7	50,3	50,0	19,6	8,24	10	N	N	N
	8	50,3	49,8	19,5	8,17	20	N	Y	N
	9	50,1	50,3	19,5	8,17	5	N	N	N
	10	49,8	50,4	19,5	8,18	10	N	N	N
	Ø	50,1	50,3	19,6	8,21	26,5			
	σ	0,3	0,3	0,3	0,1	19,4			
EAM	1	49,8	50,2	19,9	7,39	5	N	N	N
	2	50,1	49,9	20,0	7,30	5	N	N	N
	3	49,8	50,0	20,0	7,40	0	N	N	N
	Ø	49,9	50,0	20,0	7,36	3,3			
	σ	0,2	0,2	0,1	0,06	2,9			

Interpretation of Results

The comparability of the measured side lengths between scaffolds produced with the EAM and PEAM proves the general suitability of the planar drive as horizontal axis kinematics in 3D printing regarding its accuracy. The differences and deviations from the target value can be caused by fluctuations in the extrusion rate and thus the thickness of the filaments. Measurement inaccuracies can also be a cause. Further parametric studies are necessary for a detailed assessment of the dimensional accuracy of the PEAM. The reduced height of the PEAM scaffolds can be explained by the fact that the individual layers did not cool down sufficiently and were still semi liquid when the layer above was printed, causing them to sink in slightly and distort the height of the scaffold. Another reason may be the wobbling effect. Further parameter studies would be necessary to optimize this. The difference in weight between the PEAM and EAM scaffolds shows that the extrusion rate was not identical. Adjusting the screw motor speed can correct this. The increased occurrence of stringing can also be due to an excessively high extrusion rate, incorrect tempering of the material, non-optimal retraction times or a worn nozzle. In conclusion, the PoP is provided, showing that PEAM works in principle, even if further parameter optimizations would be necessary to achieve comparable quality with established 3D printers.

5.1.2 Quality Control Integrated Extrusion Additive Manufacturing

In the following, the experiments for providing the PoP for QC integrated EAM are explained. The PoP only aims to demonstrate the inline integrability of QC systems into the EAM process. No validation is carried out on whether the chosen QC approaches are suitable for sufficient quality assurance. This is already answered by the state of the art and further examination would be outside the scope of this work. Exemplary, the inline integration of an imaging station is demonstrated.

Description of Test Set-up

For the demonstration of inline imaging, the DIAMS demonstrator is used, whereby only a single mover is utilized for this experiment. The mover is assigned a job to manufacture a test scaffold. In addition, a QC interval is defined, which determines when an imaging process is to be carried out. Figure 76 shows the test setup and visualizes the simplified process flow.

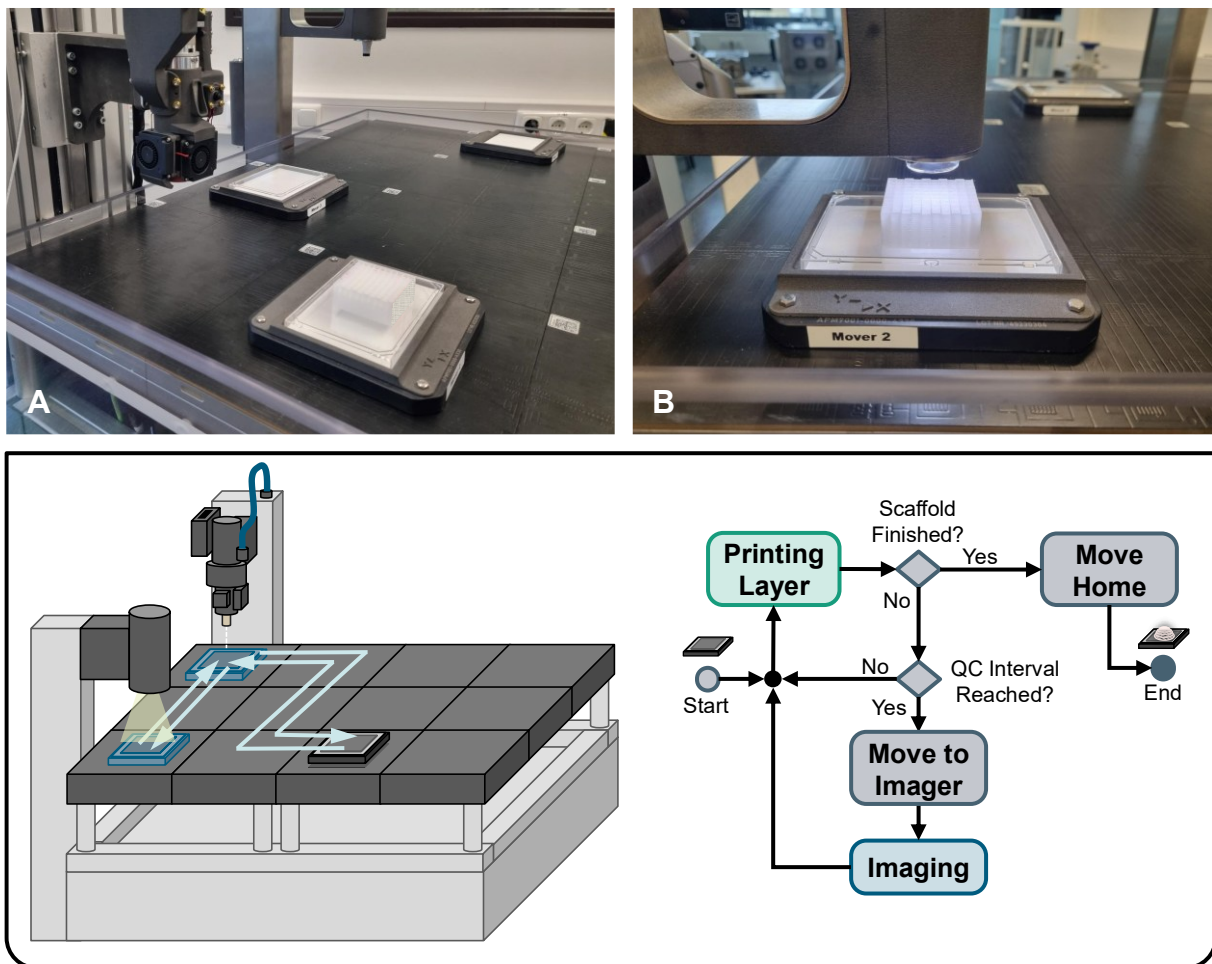


Figure 76: Test setup for EAM (A) with a digital microscope for integrated imaging (B) and a schematic visualization of the mover paths and the process flow (below)

For this PoP test, the QC interval is set to five, which indicates that after each fifth layer an imaging step will be carried out. Accordingly, the G-Code of the object is automatically split into several individual G-Code sequences. Between the G-Code sequences, the mover is instructed to move to the imaging station and trigger an imaging program. Depending on the

height of the layer to be examined, the Z-axis of the imaging station moves to the appropriate height for correct focusing. During the imaging process, the levitation height of the mover is set to zero. One or more images are captured and saved, depending on the camera settings. The mover is then levitated again and guided back to the extruder, where the next G-Code sequence is executed.

Observations and Results

During the test, it was observed that all QC steps were executed automatically at the scheduled times. Exactly 20 images were saved, which is the expected amount for a 100-layer scaffold and a QC interval of five. Figure 77 shows exemplarily one image, which was recorded by the imaging station during the experiment after 20 layers were printed.

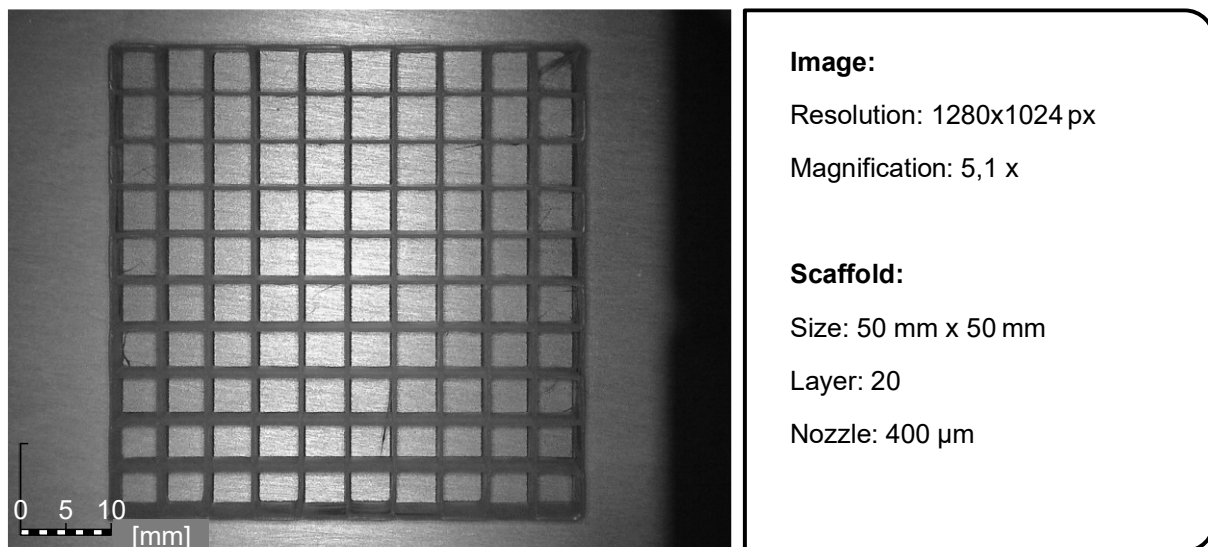


Figure 77: Exemplary image of the inline imaging station during the printing process of a test scaffold

Interpretation of Results

The observations made during the experiment provide a proof of the principle that inline integration of QC measures is possible for the developed production infrastructure. In this case, the proof of principle was demonstrated by integrating an imaging system. Based on the same concept, other QC measures can also be integrated into the printing process, such as weight measurement stations, laser profile sensors or OCT probes. This requires that the devices have the appropriate interfaces to the upper-level control software in order to realize holistic automation.

The images recorded with the imaging station allow analyses with regard to the quality attributes specified in Chapter 3.1.2. An implementation of these automatic evaluations was not carried out as part of the work and would have to be considered in subsequent investigations; compare the discussion in Chapter 6.

5.1.3 Dynamically Interconnected Multi-Agent Additive Manufacturing

In the following, the experiments to provide the PoP for dynamically interconnected multi-agent additive manufacturing are explained. The description of the experimental setup, the recording of the results and their presentation and interpretation are shown hereinafter.

Description of the Test Set-up

The developed DIAMS demonstrator is used to show that multiple free-chained movers can simultaneously execute print jobs and access shared resources such as an extruder, an imager and a scanner to process jobs dynamically and ultimately increase resource utilization. Central to this is the control algorithm, which is described in detail in Chapter 3.6.3.

Three experiments are conducted. In the first experiment, two movers are utilized; in the second experiment, three movers; and in the third experiment, four movers. Shared resources include an extruder, an imager and a scanner. To focus the investigation on the dynamic interconnection and path planning of multiple moving agents, no physical scaffolds are produced in this series of experiments. Only a processing time is simulated at each station until the mover moves to the next station. Accordingly, the assumptions that influence processing times are defined in Table 19 and hereinafter.

Table 19: Parameter settings influencing process times at the DIAMS demonstrator

Component	Parameter	Value	Unit	Description
Imager	QCInterval	5	1	Number of printed layers before an imaging step is conducted
Imager	ImagingTime	10	s	Time required for one imaging step
Scanner	ScanningTime	20	s	Time required for one scanning step
Mover	MoverVelocity	0,25	m/s	Planar drive settings for mover speed
Mover	MoverAcceleration	4	m/s ²	Planar drive settings for mover acceleration
Mover	MoverJerk	4	m/s ³	Planar drive settings for mover jerk
Extruder	ExtrusionTime	See: Figure 78	s	Time taken by the extruder to print each layer

The processing time of the extruder is determined by the object to be printed. For this, a half-spherical test scaffold with the mean values for height and diameter are chosen, as described in Chapter 4.1.1. On top of the time required for the extrusion itself, a default setup time of ten seconds is added, during which the Z-axis is positioned correctly before and after the layer is printed. The number of layers, as well as the total extrusion times for each individual layer, are calculated accordingly and displayed in Figure 78.

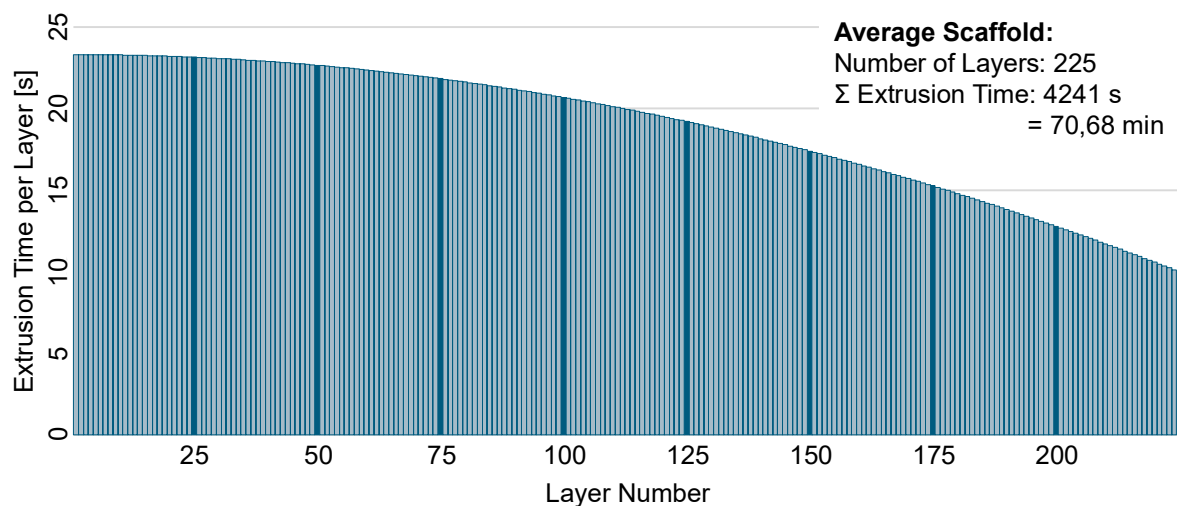


Figure 78: Bar chart showing the extrusion times for the individual printing of the layers of the half-sphere standard scaffold

Figure 79 shows the simplified process flow for the following experiments. The process blocks delay the incoming movers for the process times shown in Table 19 and Figure 78. The process flow shown applies to each mover simultaneously, with the individual interconnected stations as shared resources. In order to focus on the investigation of the intralogistics processes, these test set-up is simplified by assuming that no errors are detected by the QC tests.

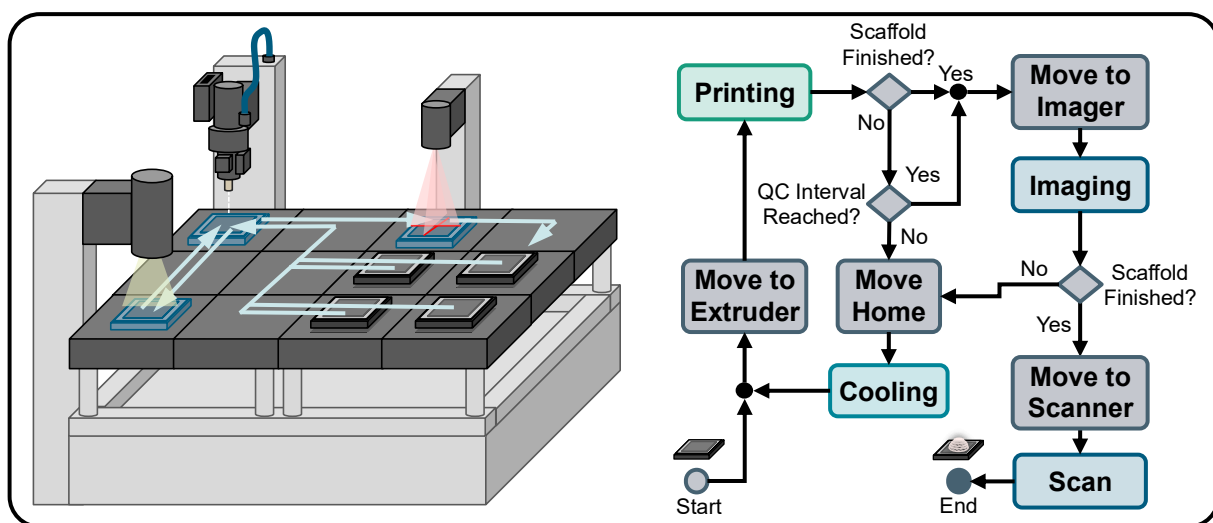


Figure 79: Process visualization including process flow diagram for individual movers

During the experiments, all process times are recorded, and the downtimes of the devices are determined accordingly. Time tracking was implemented in the PLC environment by automatically writing a time stamp individually for each mover to an array when entering and leaving a station, as well as when a waiting status is assigned. These arrays are then evaluated via further tabular calculation. In addition, the individual paths of the movers are observed during the tests and anomalies documented.

Test Conduction and Observation

The spaghetti plot in Figure 80 shows the direct connections between the individual positions that the movers occupy during the process. The intersections of these paths are indicated as knots. The number of knots can be used as a measure of complexity of the path planning. It can be observed that the path planning complexity increases with an increasing number of movers. In a preliminary Test 0 with only one active mover, no multi-agent system is represented, and the process runs completely linearly with no possible conflicts.

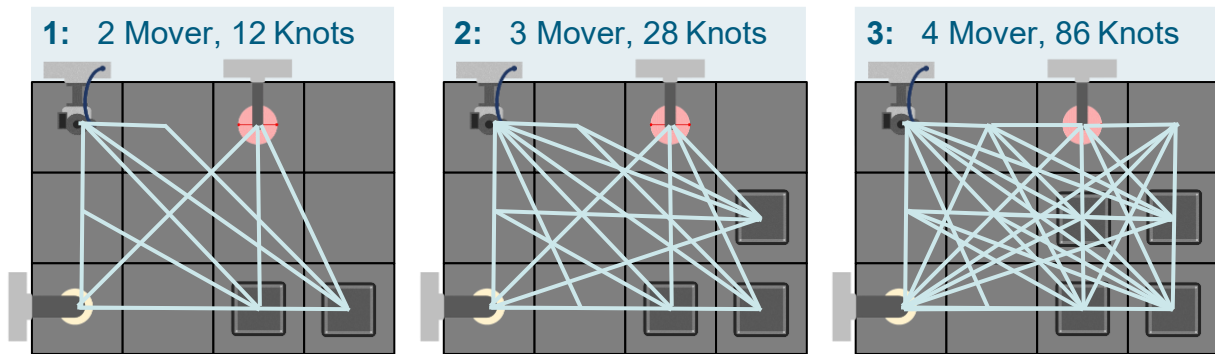


Figure 80: Spaghetti plot of mover movements with two, three and four movers

The illustrations in the spaghetti plot correspond to the observations during the experiments (Wilson, 2010). In Test 1, the movers move directly to their destination or to a corresponding waiting position in front of the destination if it is occupied. There are few blockages and thus no complex path planning to execute position changes. It is observed that the extruder is significantly more utilized than with one active mover. In Test 2, regular position changes are carried out for the movers to reach their positions, and the waiting times per mover also increase. Qualitatively, the extruder utilization appears to further increase. In Test 3, many more complex paths are executed to realize the position changes. It is assumed that the complex path planning takes time, resulting in productivity decreasing. This is verified with data in the following.

Presentation of Test Results

In order to be able to compare the approach of the dynamically interconnected multi-agent EAM with a linear standard process, the results of the three experiments are compared with the values from a previous single mover run. Figure 81 shows the recorded process times. For Test 0 with one mover, the times that the mover spends on the corresponding tasks are shown. Printing and subsequent cooling takes the most time. The mover movements and imaging only take a few minutes. The time at the scanner for the final control is negligible. There are no waiting times, as the mover is alone on the system and can run its process in a linearly way.

In Test 1, two movers are active on the system. Individually, both movers, just like the single mover in Test 0, spend the same amount of time printing, as the identical scaffold is produced by all movers. The movement times increase slightly, as does the waiting time. Ultimately, extruder utilization can be increased from 44,6 % to 83,2 %. This can also be seen in the

throughput, as the DIAMS can produce 0,71 instead of just 0,38 standard scaffolds per hour compared with the linear approach.

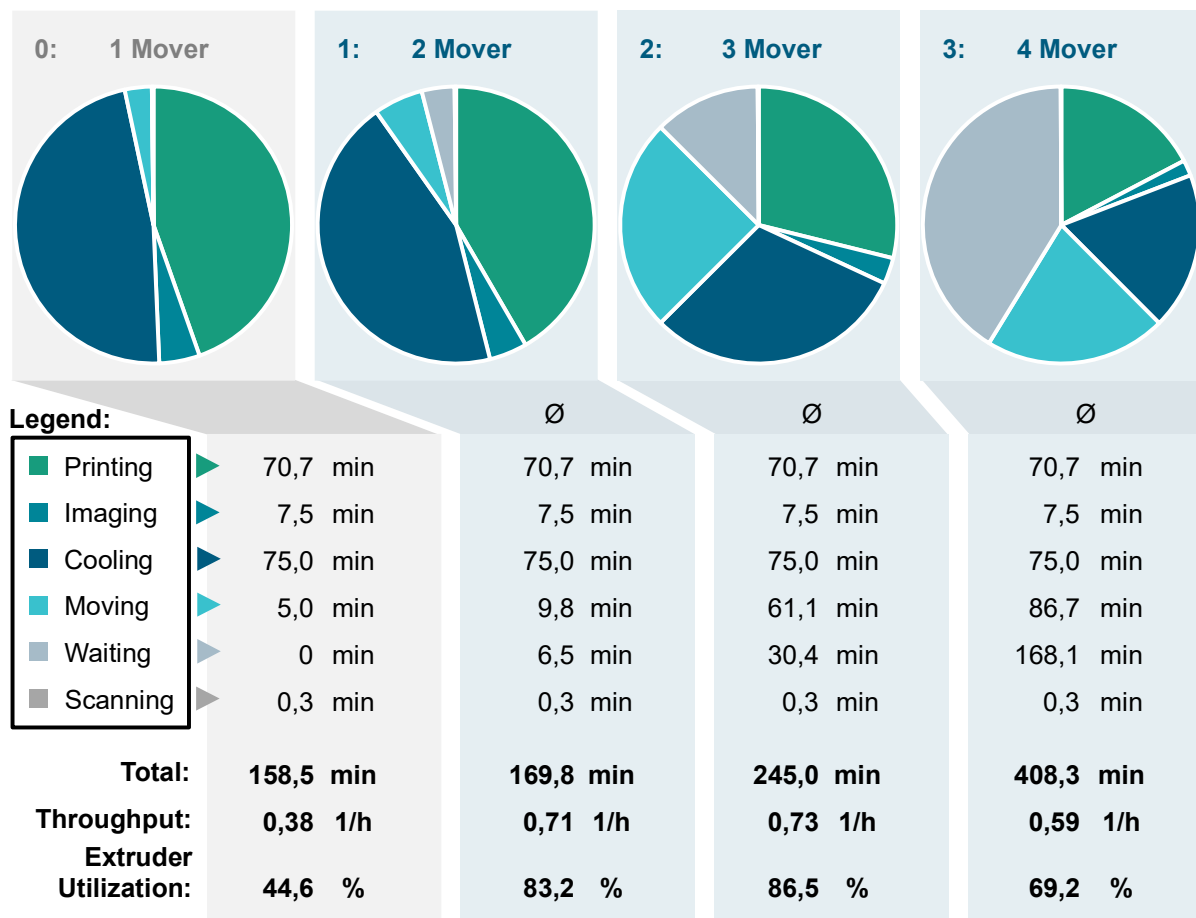


Figure 81: Presentation of the times measured on the demonstrator, which one mover spends on the respective tasks until he has finished one standard scaffold

In Tests 2 and 3, with three and four movers, the process times for printing, imaging, cooling and scanning remain identical for the movers in absolute terms. The time needed to perform the tasks increases significantly. The time a mover spends waiting also increases noticeably. Overall, the time a mover needs to complete a scaffold increases from 169,8 minutes in Test 1 to 245 minutes in Test 2 and to 408,3 minutes in Test 3. In Test 3, it is observed and measured that the movers spend most of their time waiting. The highest extruder utilization of 86,5 % and the highest production throughput of 0,73 scaffolds per hour were measured in Test 2. It is noticeable that the extruder utilization in Test 3 decreased significantly compared to Test 2, although more movers were available. Consequently, the throughput also decreased significantly.

Interpretation of Results

The extruder utilization increases from Test 0 to Test 1 as expected, since the extruder can now also be used by a mover when the other mover must pause for cooling. Adding a third mover in Test 2 only slightly increases extruder utilization. This depends heavily on the shape of the print object and the print speed. If the object consists of layers that require only a very

short printing time or are printed very quickly, the ratio between cooling time and printing time is higher, so more movers can be used to maximize extruder utilization. In this example, the ratio is between two and three movers per extruder for maximum utilization. A utilization of 100 % cannot be achieved practically because after completing a printing step, the mover at the extruder and the next mover must swap places. This exchange process takes a certain amount of time, which does not allow the extruder to be used and thus reduces the utilization rate.

The increase in mover waiting time from Test 1 to Test 2 can be explained by the fact that the extruder and imager stations can now be occupied by movers at the same time, so that one mover has to wait in any case. This increases the average waiting time considerably. As was already suspected during the observation of the tests, the waiting time increases drastically in Test 3 with four active movers and the extruder utilization decreases significantly. This is, on the one hand, because the point of maximum extruder utilization has already been exceeded, which is in between two and three movers per extruder. On the other hand, adding more movers beyond this ratio has a counterproductive effect, since a higher mover density on the system increases the complexity of the path planning, as illustrated in Figure 80. Both the movement times and the waiting times until a mover has released a position are longer.

In addition, the tests showed that a dynamically interconnected multi-agent EAM approach can achieve higher system utilization rates than linear approaches. However, this added value is heavily dependent on the defined use case. In order to be able to make a more general statement, further tests including multiple extruders would be necessary to better investigate the influence of shared resources. This is discussed further in Chapter 6. The dimensions of production also have a major influence on the performance of the SPIDA. Therefore, it is proceeded to use a digital representation of SPIDA to investigate other production scenarios.

Interim Conclusion

The sub research question **SRQ2 “How can the process steps be automated for a scalable production of personalized scaffolds?”** was answered in Chapter 3.8. With the validation results from this Chapter 5.1 the answer is verified. The core aspects of the SPIDA concept, consisting of the PEAM, the integrated quality control and the dynamically interconnected multi-agent control, were each demonstrated in practical experiments.

5.2 Comparative Studies between Digital Model and Physical Demonstrator

In this chapter, the physical demonstrator of the production infrastructure and its digital representation are compared to verify a realistic digital imitation of the physical system. The results of this comparison can then be used to answer SRQ3 and to conduct further simulation studies, compare Figure 82.

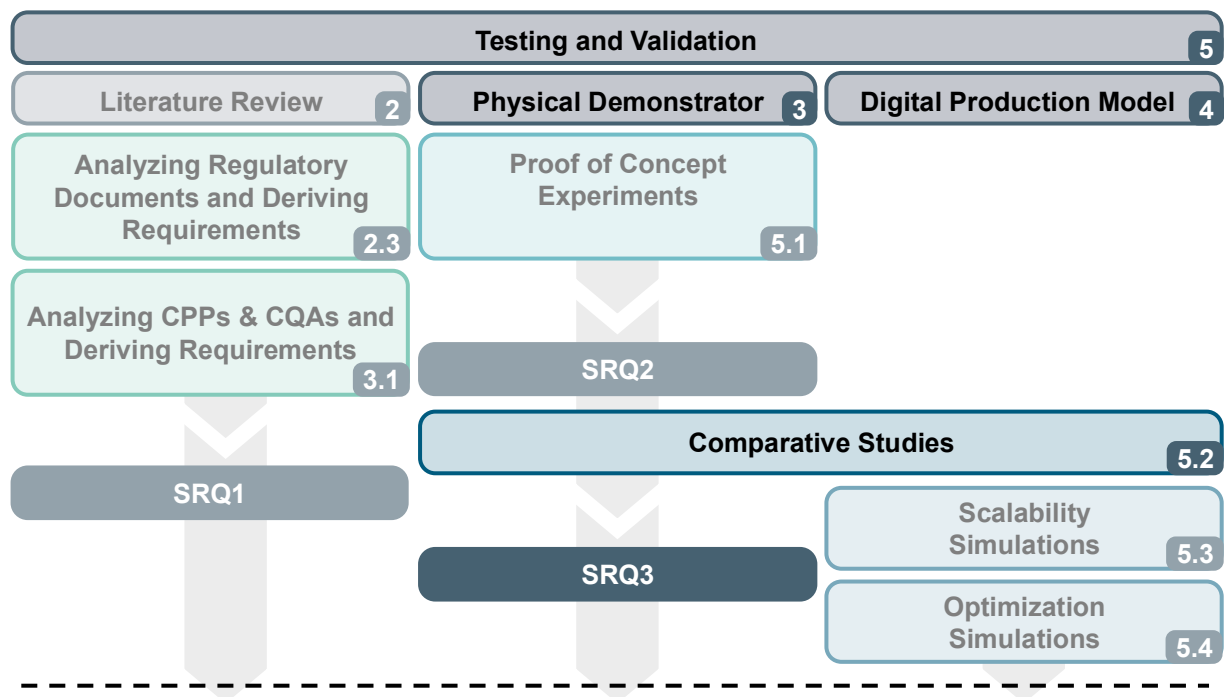


Figure 82: Segment of the testing and validation structure with focus on the comparative studies between the physical demonstrator and the digital production model.

The comparative study uses the data generated within the test series from Chapter 5.1.3 about dynamically interconnected multi-agent EAM with all its process times that were recorded to compare them with the data resulting from the simulations from the digital model. Therefore, the digital model is configured to be comparable to the physical counterpart. This includes the adjustment of the layout, the positioning of the stations and movers, and the home position, as well as the configuration of all process parameters. With the configured model, the comparative simulations are then carried out and the corresponding data is recorded. The process data of the scenarios are pairwise compared and analyzed for statistically significant differences.

Model Configuration

When developing the digital model in Chapter 4, comparability with the physical prototype, developed in Chapter 3.7, was considered. A corresponding parameterization of the system was already presented in Chapter 4.4 and is used in the following experiments. The DiSPIDA model can be easily adapted to the demonstrator in terms of its mechanical form. For this purpose, the same tile configuration of 3x4 tiles is used and the stations in the form of the imager, scanner and extruder submodels are connected accordingly to the right tiles, as shown in Figure 83.

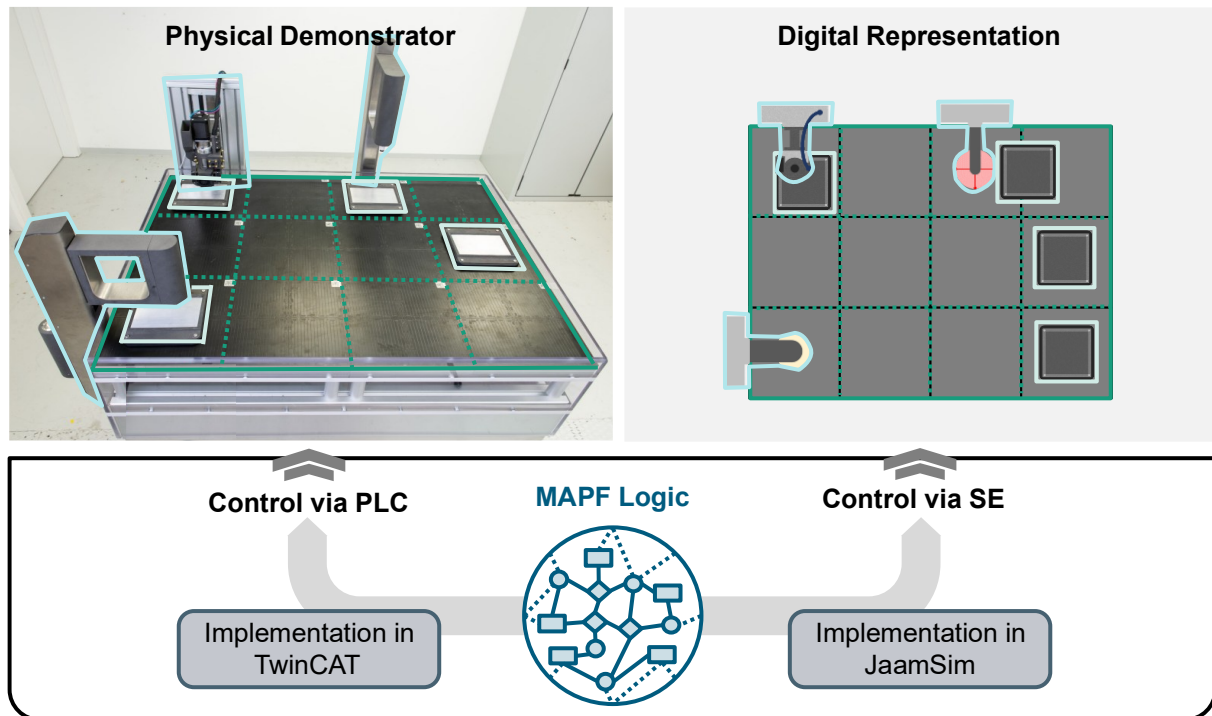


Figure 83: Laboratory setup of the physical demonstrator and its digital image, implemented in JaamSim

On the software side, the systems differ in that the demonstrator is controlled via the TwinCAT PLC, while the digital model exists in the simulation environment (SE) and is controlled via the logics implemented in JaamSim. Both cases are founded on the same CBS-based MAPF logic, although the way of implementation differs due to the different development environments, compare Chapter 3.6.3 and Chapter 4.3.2. Another aspect that influences the comparability of the systems is the deficiency of the developed digital model to simulate accelerated movements of the movers. Instead, all movers always move at a constant speed. Since the movers of the demonstrator have an implemented speed of 0,25 m/s and an acceleration of 4 m/s², this results in a delay of 0,06 s per path due to acceleration and deceleration compared to the simulation with a constant 0,25 m/s mover speed. This difference is compensated by delaying the mover travel times accordingly in the model. Based on these settings, the experiments presented in Chapter 5.1.3 are simulated with the DiSPIDA model in the following. The virtual object to be produced is therefore also the defined standard half-sphere scaffold. Five replications of the simulation are conducted, and the process times are recorded automatically, analogous to the physical experiments.

Simulation Results

In Table 20, the process times measured on the real physical demonstrator are compared with the process times from the correspondingly configured DiSPIDA simulation. On the demonstrator, the process times on how long a mover stays at a station, were recorded and output automatically by the PLC. These time recordings could be reproduced exactly for each run as long as the input parameters stay consistent because, unlike in the simulation, no varying random seeds were used that could lead to a variation in the paths. Instead, all paths were always identical under the same conditions. Accordingly, no replicates of the physical

experiments are necessary. For the simulation, varying random seeds can affect the path planning. The mean values ($\bar{\theta}$) of five replications and their standard deviation (σ) are given.

Table 20: Comparison of the simulated and physically measured process times for a DIAMS with one, two, three and four active movers

Average Mover Process Time per Produced Scaffold [min]								
		Printing Time	Imaging Time	Scanning Time	Waiting Time	Cooling Time	Moving Time	Total Production Time
1 Mover	Real	70,67	7,50	0,33	0,00	75,00	5,00	158,50
	Simulation $\emptyset$	70,67	7,50	0,33	0,00	75,00	5,08	158,59
	Simulation σ	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2 Mover	Real	70,67	7,50	0,33	6,50	75,00	9,80	169,80
	Simulation $\emptyset$	70,67	7,50	0,33	6,61	75,00	9,95	170,07
	Simulation σ	0,00	0,00	0,00	0,26	0,00	0,43	0,69
3 Mover	Real	70,67	7,50	0,33	30,37	75,00	61,08	244,95
	Simulation $\emptyset$	70,67	7,50	0,33	30,64	75,00	60,96	245,11
	Simulation σ	0,00	0,00	0,00	0,96	0,00	0,43	1,39
4 Mover	Real	70,67	7,50	0,33	168,08	75,00	86,72	408,30
	Simulation $\emptyset$	70,67	7,50	0,33	167,75	75,00	86,10	407,36
	Simulation σ	0,00	0,00	0,00	6,83	0,00	1,68	8,50

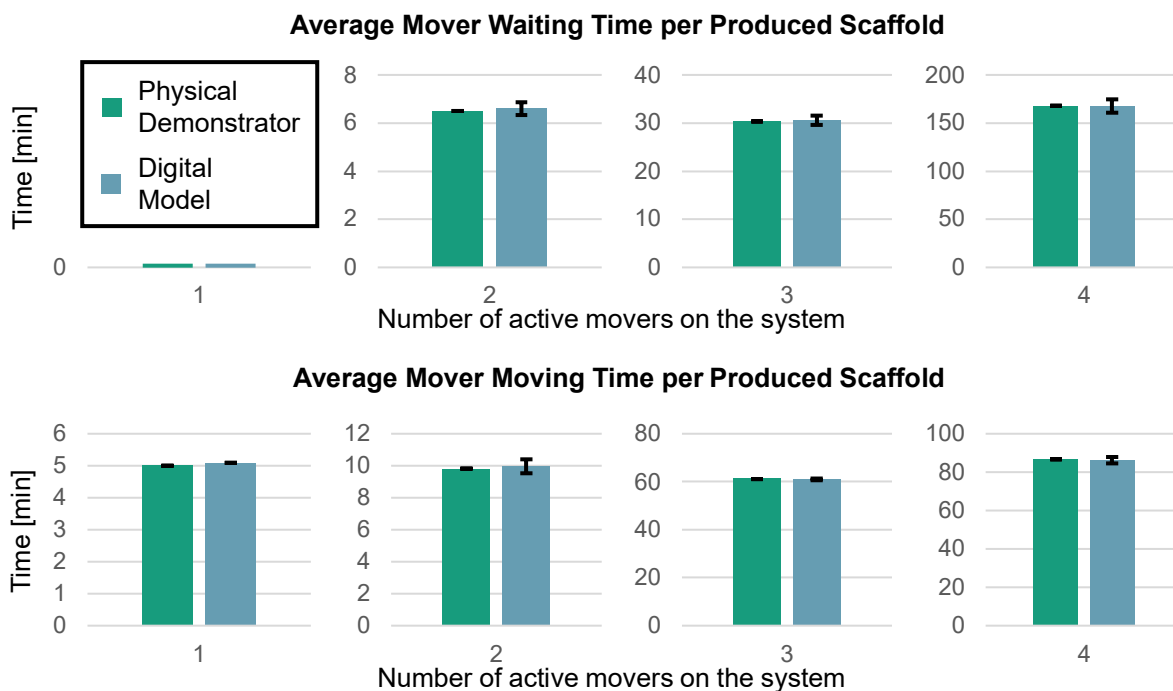


Figure 84: Comparison of non-identical process times from simulation and measurements on the physical demonstrator

It is noticeable that, for the recorded printing, imaging, scanning and cooling times, no difference was detected between the simulation and the real measurements on the system. Also, the standard deviations of the simulation runs are 0, meaning that the process times are replicated accurately.

The only process times where differences between the real and simulated systems can be identified are the waiting and moving times. Figure 84 illustrates these differences in the form of paired bar charts. For one active mover, the average mover waiting time per scaffold is 0 for both the real system and the simulation. For all other process times, the values of the physical demonstrator differ only slightly from those of the digital model. In all case, the values of the demonstrator are within the standard deviation interval of the simulation values.

Interpretation of Results

The fact that the measured and simulated values for the printing, imaging, scanning and cooling times are identical, is due to the fact that these values were set for the demonstrator via the PLC and can then be executed reproducibly. The individual process times are then recorded again by the PLC during the tests. These values were then used to configure the simulation model. The simulation can then also replicate these process times precisely.

The variance of the simulation values for the moving and waiting process times, which are dependent on each other, is based on the fact that random decisions are implemented within the MAPF algorithm, when a mover can take two equivalent paths to reach a target. In each replication, these random decisions vary. The path decisions then lead to the fact that all other subsequent paths can differ as well, which then has an influence on the moving and also on the waiting times of a mover within a simulation run. The standard deviations in Table 20 and Figure 84 indicate the ranges in which these variations occur. Conducting a two-tailed t-test to determine the probability that each measured value from the demonstrator belongs to the corresponding series of simulated values, on average, results in a probability of 78,3 %. The maximum and minimum values are 96,4 % and 68,8 %. The comparison studies ultimately show that the appropriately configured DiSPIDA simulation can replicate the static process times exactly and that the MAPF motion processes can also be realistically modeled.

Interim Conclusion

In Chapter 1.3, sub research question **SRQ3 “How can an automated scaffold production infrastructure be digitally modeled?”** is stated. In Chapter 4.5, this question is answered with the developed DiSPIDA simulation model. In this chapter, it is verified that the model can realistically reproduce reality. Since this comparison only refers to the demonstration system and not to a complete production system, the limitations of this comparison are further discussed in Chapter 6.

5.3 Scalability Simulations on a Digital Production Model

In this chapter, the developed digital production model DiSPIDA is used to conduct a scalability study, as visualized in the methodology in Figure 85. In this case, scaling refers to production throughput, in other words, the number of personalized scaffolds produced per unit of time. The product type and settings remain the same throughout all simulation runs. In terms of the extruders and QC stations used, a horizontal scaling approach is pursued, also known as a scale-out approach. This means that further devices are added to increase performance, rather than replacing devices with more performant ones, which would be described as vertical scaling or scale-up (Michael et al., 2007).

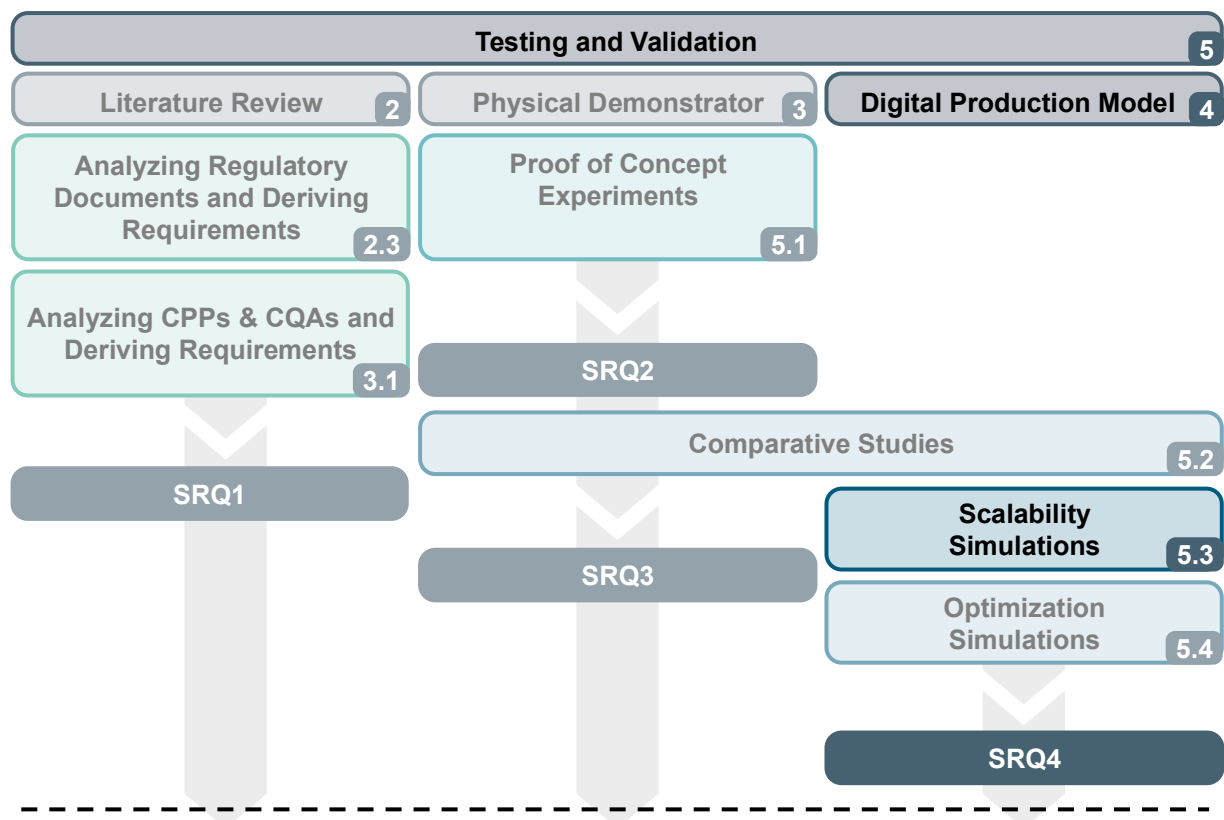


Figure 85: Segment of the testing and validation structure with focus on the scalability simulations with the digital production model

The methodical approach for conducting the simulation study is based on the process models of Rabe et al. “Verification and Validation for Simulation in Production and Logistics” (Rabe et al., 2008). Therefore, problem-relevant hypotheses are formulated, scenarios for testing are derived, simulations for data collection are carried out and interpreted to answer the hypotheses. This approach is illustrated in Figure 86 and is applied in the following subchapters.

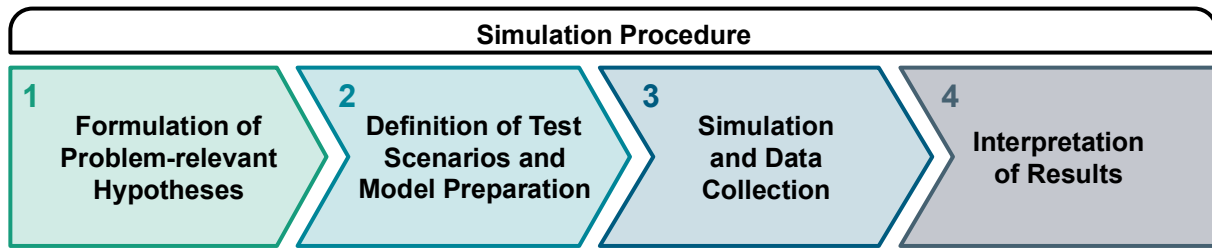


Figure 86: General approach for conducting the simulation experiments

Three hypotheses are formulated and examined. Hypothesis 1 addresses the scaling in terms of production throughput as a function of the system footprint. Hypothesis 2 addresses the influence of parallelization and decoupled production on throughput scaling. Hypothesis 3 compares the scalability of the SPIDA concept with that of conventionally automated systems.

5.3.1 Production Throughput in Relation to the System Footprint

In the following, the effect of increasing the throughput of the scalable production infrastructure for dynamically interconnected AM on the areal footprint of the system is investigated. The following hypothesis is formulated for this purpose:

Hypothesis 1

» The SPIDA production throughput scales in relation to the system footprint over-proportionally «

The hypothesis states that the quotient of the production throughput of a system P and the area of this system A increases by scaling the system to a larger production scenario. In practice, this means that the larger the production plant is designed, the more space-efficient the production operates.

Test Scenarios and Model Preparation

Six DiSPIDA production models are implemented, each of which depicts a differently scaled production scenario, as shown in Figure 87. For overview purposes, the storages and robots have been omitted from the illustrations of the production layouts. However, the peripheral systems were taken into account for calculating the footprint using equation 8.

The following criteria were taken into account to ensure comparability of the scenarios: First, the mover-extruder ratio is kept constant at 2:1 for each scenario. Second, the number of imagers is increased by one as soon as a bottleneck occurs. Such a bottleneck can be recognised when the average 'WaitingForImager' state time increases significantly compared to other scenarios. Thirdly, the stations were arranged at the edges of the system, with two movers in close proximity to each extruder. Apart from Scenario 1, the width of the system was kept constant in order to avoid empty central areas. Fourthly, all process parameters such as mover speed, product parameters and error rates are kept consistent for all scenarios. Detailed information can be found in Chapter 4.4 on parameterization of the simulation model. The simulated production time is 6 days, which corresponds to 144 hours.

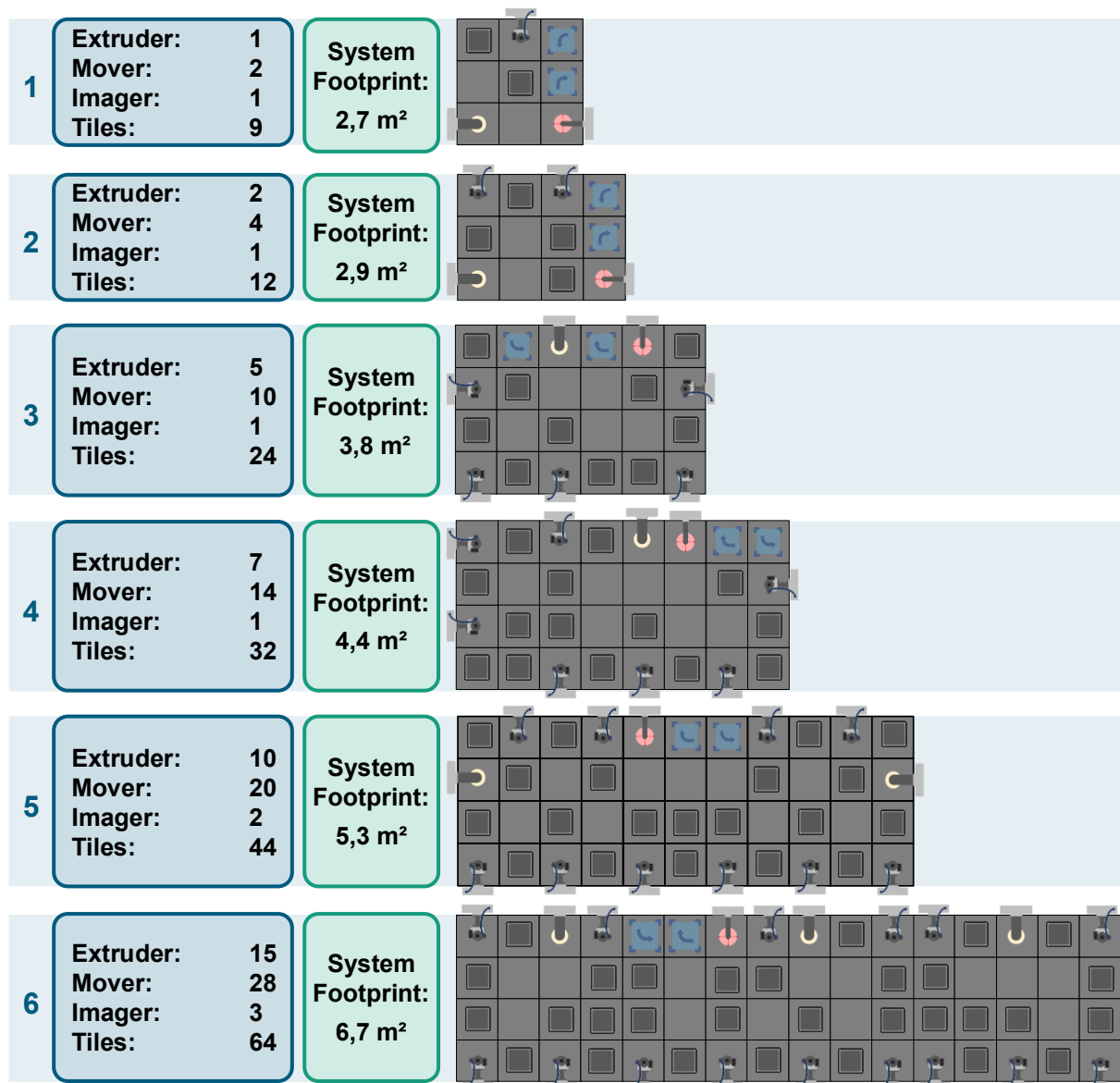


Figure 87: Comparison of the configuration of differently scaled production scenarios regarding system footprint and utilized equipment

Simulation and Data Collection

Table 21 shows selected data recorded from the simulations of the six production scenarios, whose configuration is shown in Figure 87. Five replications were carried out for each scenario and the mean values are shown. The focus of these results is on the values for produced scaffolds, the system footprint and its quotients. The other values can be used to interpret the results. Figure 88 supplements this table with a corresponding graphical illustration.

Table 21: Simulation results for differently scaled production scenarios

ProductionScenario	Unit	1	2	3	4	5	6
Produced Scaffolds	1	43	120,2	376	481	638,8	1041,8
Defect Scaffolds	1	4,0	11,8	36,6	46,4	60,6	96,8
System Footprint	m²	2,7	2,9	3,8	4,4	5,3	6,7

Production Throuput per Area	1/m ²	15,9	41,4	98,9	109,3	120,5	155,5
Number of Active Extruders	1	1	2	5	7	10	15
Number of Tiles	1	9	12	24	32	44	64
Number of Active Movers	1	2	4	10	14	20	30
Number of Active Imagers	1	1	1	1	1	2	3
Number of Active Scanners	1	1	1	1	1	1	1
Average Total Production Time	min	190,0	268,2	215,6	235,3	252,5	232,7
Average "Printing" Time	min	89,7	88,4	88,0	88,1	87,9	88,1
Average "Scanning" Time	min	0,3	0,3	0,3	0,3	0,3	0,3
Average "Imaging" Time	min	9,2	9,2	9,2	9,2	9,2	9,2
Average "Moving" Time	min	15,4	27,9	30,1	32,3	28,4	30,8
Average "WaitForExtruder" Time	min	0,0	62,2	8,6	15,6	31,6	18,4
Average "WaitForScanner" Time	min	0,0	0,1	0,0	0,0	0,5	0,7
Average "WaitForImager" Time	min	0,0	4,7	3,9	14,4	19,1	9,7
Average "WaitForRobot" Time	min	0,2	0,2	0,3	0,3	0,3	0,3
Average "RoboticTransport" Time	min	0,2	0,2	0,2	0,2	0,2	0,2
Total Printing Time	d	1,5	4,1	5,0	4,6	4,2	4,6
Extruder Utilization Percentage	%	24,4	67,6	84,1	76,8	71,2	77,4
Average Mover Waiting Percentage	%	0,1	25,1	6,0	12,9	20,4	12,5
Average Mover Moving Percentage	%	8,1	10,4	14,0	13,7	11,2	13,2

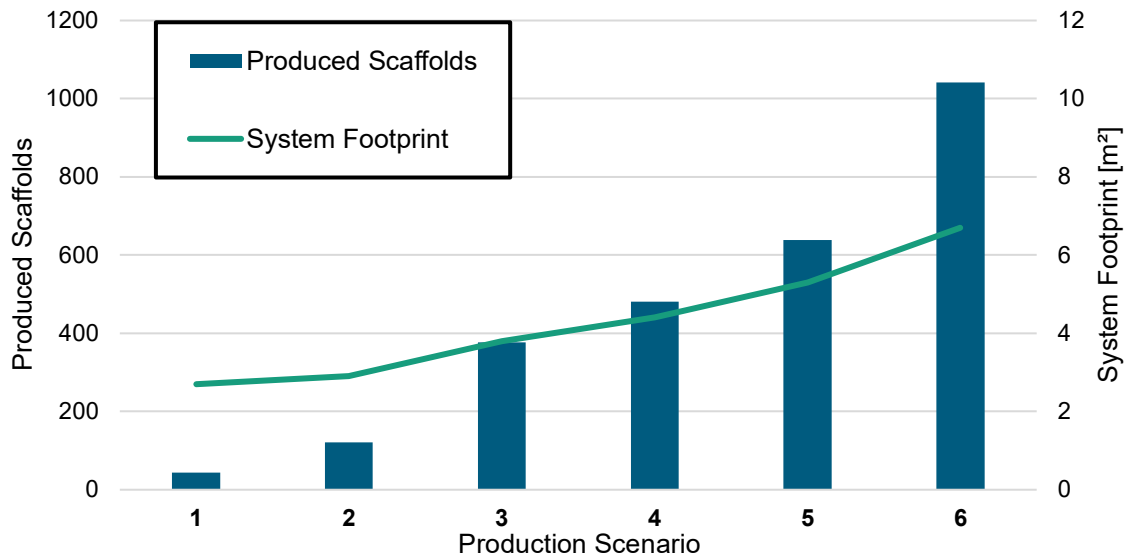


Figure 88: Comparison of production throughputs and system footprint for different production scenarios

The data obtained shows that the number of scaffolds produced increases from production Scenario 1 to 6, but so does the area of the production plant. When looking at the P/A quotient, it can be seen that it also increases steadily. When comparing Scenario 1 (15.9 1/m²) and Scenario 6 (155.5 1/m²), it can be seen that almost 10 times as many scaffolds can be produced per square meter of production area. One noteworthy aspect that can be observed is

the comparatively high extruder utilization in Scenario 3 (84,1 %) compared to Scenarios 2, 4, 5 and 6 (<77,4 %).

Interpretation of Results

The steady increase in the P/A ratio confirms that the production throughput increases over-proportionally in relation to the system footprint. Hypothesis 1 is therefore supported. The statement that the larger the production plant is designed, the more space-efficient the production would operate, is verified for the production scenarios and framework conditions investigated.

The noticeably high extruder utilization in Scenario 3 can be traced back to different reasons. On the one hand, the percentage waiting time in Scenario 3 is significantly lower than in the next most similar Scenarios 2 and 4. This may be because the waiting times in front of the imaging station are longer in Scenario 4 because more movers are served by one imager compared to Scenario 3. This can also be seen in the “WaitForImager” Average Time of the movers in Table 21. The addition of another imager in Scenarios 4, 5 and 6 could thus further increase their performances. On the other hand, the difference between Scenarios 2 and 3 can be explained by the fact that the open space-mover ratio is different. Scenario 2 has only two permanently free tiles out of twelve tiles, which is 16,7 %. Scenario 3 has five permanently free tiles out of a total of 24 tiles, which is 20,8 %. The larger the open space-mover ratio, the less complex and time-consuming the intralogistics path finding maneuvers of the movers are in order to reach their respective destinations without blocking other movers. In all cases, however, a slightly different arrangement of the stations and movers could have a noticeable effect on waiting times and extruder utilization.

5.3.2 Influence of Dynamic Interconnection on System Utilization

In the following, the effect of the dynamically interconnected multi-agent approach on the production performance is investigated. The following hypothesis is formulated for this purpose:

Hypothesis 2

» The dynamically interconnected multi-agent additive manufacturing approach of SPIDA enables higher device utilization compared to linearly automated systems «

This hypothesis states that decoupling the manufacturing process, where multiple movers can work at respective stations, leads to higher utilization of the equipment. This would have the practical consequence that the available hardware is used more efficiently for production.

Test Scenarios and Model Preparation

To investigate the hypothesis, the dynamically interconnected multi-agent approach of SPIDA is compared with various linear production approaches. For this purpose, a total of four different production scenarios are implemented on DiSPIDA. Figure 89 shows the configurations of the simulated scenarios.

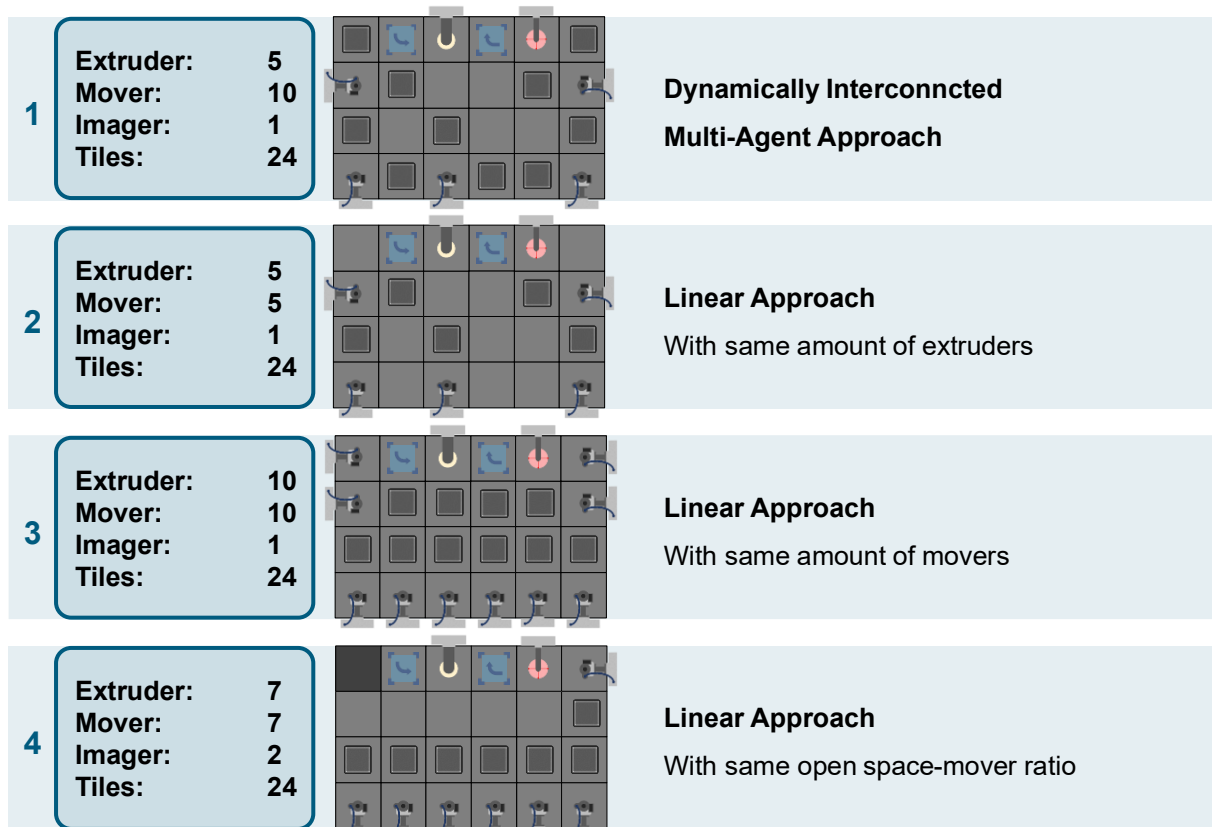


Figure 89: Comparison of the configuration of production scenarios with a dynamically interconnected multi-agent approach and linear production approaches

Scenario 1 has already been presented in Chapter 5.3.1 and is also used to investigate this hypothesis. Scenario 2 simulates on the same system footprint with the same number of extruders as in Scenario 1 but without a multi-agent interconnection to the extruders. Instead, only one mover works on one extruder. Scenario 3 also simulates on the same system footprint

but with the same number of movers and an increased number of extruders compared to Scenario 1. Scenario 4 simulates with the same open space-mover ratio. Compared to Scenario 1, the number of movers is reduced, and the number of extruders remains the same. To achieve the same open space-mover ratio, one tile was removed, so the production area is slightly reduced. Analogous to the simulations in Chapter 5.3.1, all process parameters and simulation conditions are kept consistent for all scenarios.

Simulation and Data Collection

Table 22 shows selected data, recorded from the simulations of the four production scenarios, whose configuration is shown in Figure 89. Five replications were carried out for each scenario and the mean values are shown. The focus of these results is on the values for produced scaffolds, extruder utilization percentage and the numbers of the different stations.

Table 22: Simulation results for different scenarios following linear and dynamically interconnected production approaches

Production Scenario	Unit	1	2	3	4
Produced Scaffolds	1	376	216,6	395	295,2
Defect Scaffolds	1	36,6	21,6	37,2	28,4
Number of Active Extruders	1	5	5	10	7
Number of Tiles	1	24	24	24	24
Number of Active Movers	1	10	5	10	7
Number of Active Imagers	1	1	1	1	1
Number of Active Scanners	1	1	1	1	1
Average Total Production Time	min	215,6	187,4	205,5	191,2
Average "Printing" Time	min	88,0	87,8	88,1	87,4
Average "Scanning" Time	min	0,3	0,3	0,3	0,3
Average "Imaging" Time	min	9,2	9,1	9,2	9,1
Average "Moving" Time	min	30,1	12,7	13,4	13,2
Average "WaitForExtruder" Time	min	8,6	1,1	12,4	2,5
Average "WaitForScanner" Time	min	0,0	0,0	0,0	0,0
Average "WaitForImager" Time	min	3,9	1,0	6,7	3,1
Average "WaitForRobot" Time	min	0,3	0,3	0,3	0,3
Average "RoboticTransport" Time	min	0,2	0,2	0,2	0,2
Total Printing Time	d	5,0	2,9	2,6	2,8
Extruder Utilization Percentage	%	84,1	48,4	44,0	46,8
Average Mover Waiting Percentage	%	6,0	1,3	9,4	3,1
Average Mover Moving Percentage	%	14,0	6,8	6,5	6,9

It is noticeable that Scenario 3 achieves the highest throughput with 395 scaffolds, closely followed by Scenario 1 with 376 scaffolds. Significantly less was produced in Scenario 4 and the least in Scenario 2 with 216,6 scaffolds. At 84,1 %, the extruder utilization rate in Scenario 1 is significantly higher than in all other scenarios, where the values are between 44 % and 48,4 %. There are noticeable differences between Scenario 1 and Scenarios 2-4 in the

Average “Moving” Time. In Scenario 1, on average, the movers took 30,1 minutes for all movements from position to position, which is more than twice as long as in the other scenarios. Also noticeably high is the Average “WaitForExtruder” and “WaitForImager” Time in Scenario 3.

Interpretation of Results

The fact that the most scaffolds were produced in Scenario 3 is due to having the most extruders (10 units) in operation. However, throughput is only slightly higher than in Scenario 1 because the same number of movers were operating, dynamically interconnected with the extruders so that two movers can serve one extruder. This also explains the significantly higher extruder utilization in Scenario 1. In Scenarios 2-4, the extruder is always unused when a mover moves with a printed layer to the imaging station or for cooling down. In Scenario 1, this interim time can be used by another mover to print another layer.

Another effect that can be explained by the dynamically interconnected multi-agent approach in comparison to the linear approach is the significant increase in the Average “Moving” Time. Since there is a surplus of movers in comparison to extruders in Scenario 1, there are regular waiting times in front of the extruders. If two movers then have to change position so that the next mover can carry out its printing process, the movers may have to drive longer, more complicated paths to complete this change of position.

The noticeably high average “WaitForExtruder” and “WaitForImager” time in Scenario 3 can be explained by the fact that no open space is available in this scenario. Every single tile of the planar drive is occupied by a station or a mover home position. Even though the unused tiles of the individual stations are used for path planning for the movers while the simulation, the movement density on the system is very high, so that movers are regularly blocked by other movers, which leads to increased waiting times at the stations.

Overall, the hypothesis that SPIDA's dynamically interconnected multi-agent AM approach enables higher device utilization compared to linearly automated systems, can be confirmed. However, if the production should be designed to achieve maximum throughput, and the number of available extruders is unlimited, a linear automation may be more suitable. To confirm or refute this, one would have to expand Scenario 1 with additional extruders and examine whether the dynamically interconnected approach can achieve higher throughputs than in Scenario 3.

5.3.3 Comparison to Conventionally Automated Production Systems

In the following, the SPIDA concept is compared with conventional linear automation and examined in terms of scalability. The following hypothesis is formulated for this purpose:

Hypothesis 3

» SPIDA requires a smaller footprint and less equipment than a conventionally automated production system to achieve the same production throughput «

This hypothesis states that, when comparing the automation approach of SPIDA, which is based on a planar drive system, with conventional automation using robots on linear axes to carry out the transportation steps, the SPIDA approach is more efficient in terms of production throughput and required system footprint.

Test Scenarios and Model Preparation

The SPIDA Scenarios 1 to 6 whose configurations were already shown in Figure 87 are compared with further scenarios, which configurations are shown in Figure 90.

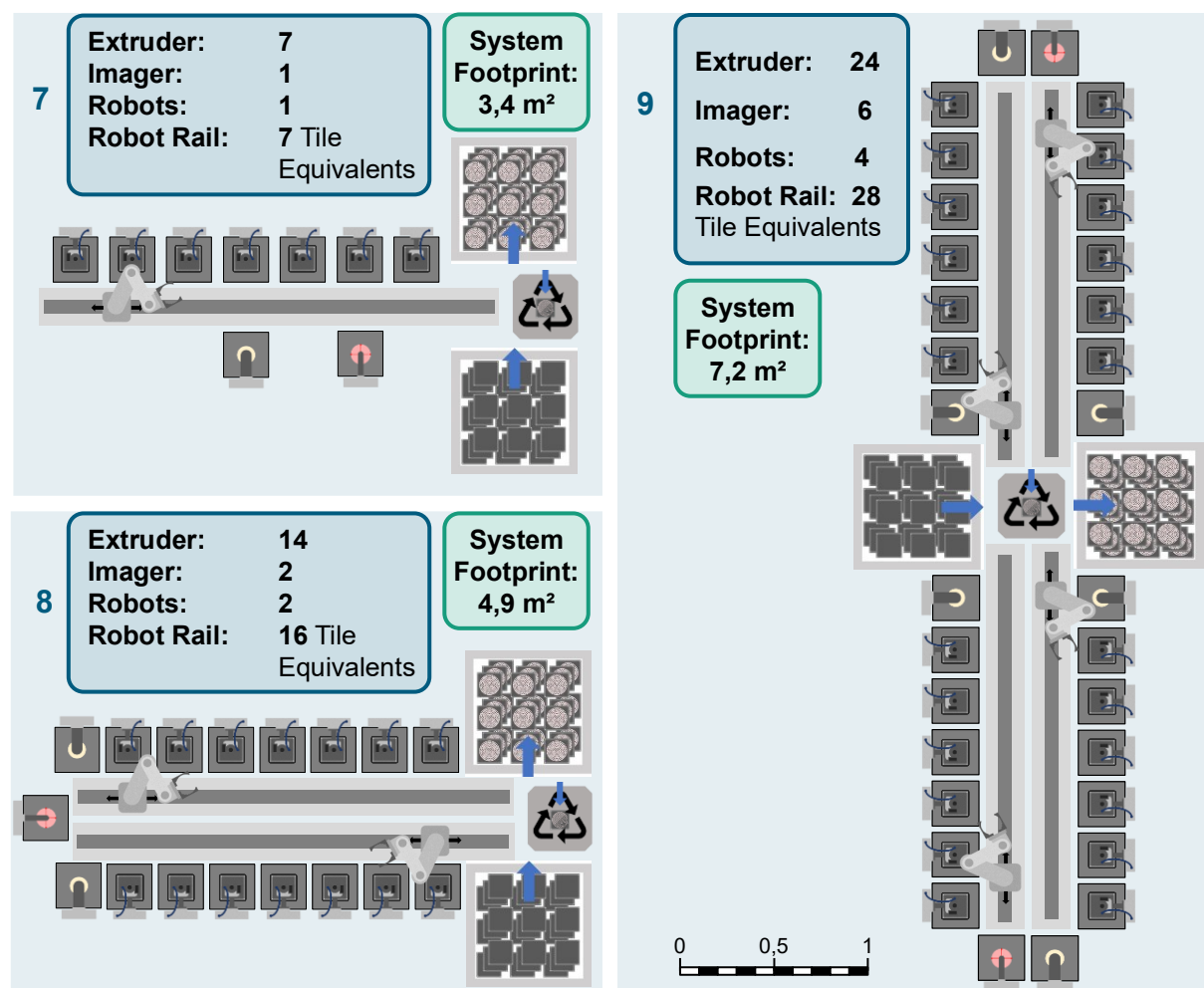


Figure 90: Model configurations of differently scaled conventionally automated production scenarios for scaffold manufacturing

The same imagers, extruders, scanners, applicators and separator submodels were used for Scenarios 7 to 8. Instead of the planar drive system, robots were used for linear product transport. In Scenario 7, the robot is responsible for seven extruders and carries out all transport routes, for example to the imager, one after the other. The First-In-First-Out (FIFO) principle applies regarding the robot requests. Scenario 8 is a duplication of Scenario 7. Scenario 9 is a duplication of Scenario 8, whereby each of the four robots serves only six instead of seven extruders. It is implemented that the robot on the linear axis has the same speed as the movers on the planar drive. In addition, for each travel path, five seconds each are set to be required for the removal and placement of a scaffold substrate. All parameters that influence the process times of the stations are kept consistent, the same as in the SPIDA Scenarios 1 to 6.

Simulation and Data Collection

Table 23 shows selected data recorded from the simulations of the six production scenarios already shown in Table 21 and three further scenarios whose configuration is shown in Figure 90. Five replications were carried out for each scenario and the mean values are shown. The focus of these results is on the values for produced scaffolds, the system footprint and its quotients. Figure 91 visualizes the key findings of this simulation data.

Table 23: Simulation results for different production scenarios comparing the SPIDA approach (Scenarios 1-6) with conventional automation approaches (Scenarios 7-8). The values for Scenarios 1 to 6 are shown in a smaller font, as they can also be found in Table 21.

Production Scenario	Unit	1	2	3	4	5	6	7	8	9
Produced Scaffolds	1	43	120	376	481	639	1042	249,2	496	885,6
Defect Scaffolds	1	4	12	37	46	61	97	24,6	60	88,8
System Footprint	m ²	3	3	4	4	5	7	3,4	4,9	7,2
Production Throuput per Area	1/m ²	16	41	99	109	121	155	73,3	101,2	123,0
Number of Active Extruders	1	1	2	5	7	10	15	7	14	24
Number of Tiles	1	9	12	24	32	44	64	7	16	28
Number of Active Movers	1	2	4	10	14	20	30	7	14	24
Number of Active Imagers	1	1	1	1	1	2	3	1	2	4
Number of Active Scanners	1	1	1	1	1	1	1	1	2	2
Average Total Production Time	min	190	268	216	235	252	233	226,8	228,0	218,7
Average "Printing" Time	min	90	88	88	88	88	88	87,7	87,7	88,1
Average "Scanning" Time	min	0	0	0	0	0	0	0,3	0,3	0,3
Average "Imaging" Time	min	9	9	9	9	9	9	9,1	9,2	9,1
Average "Moving" Time	min	15	28	30	32	28	31	0,0	0,0	0,0

Average "WaitForExtruder" Time	min	0	62	9	16	32	18	72,2	72,9	72,4
Average "WaitForScanner" Time	min	0	0	0	0	1	1	0,0	0,0	0,0
Average "WaitForImager" Time	min	0	5	4	14	19	10	0,0	0,0	0,0
Average "WaitForRobot" Time	min	0	0	0	0	0	0	35,6	35,7	26,5
Average "RoboticTransport" Time	min	0	0	0	0	0	0	21,9	22,1	22,2
Total Printing Time	d	1	4	5	5	4	5	2,4	2,4	2,5
Extruder Utilization Percentage	%	24	68	84	77	71	77	39,7	40,3	41,4
Average Mover Waiting Percentage	%	0	25	6	13	20	13	47,5	47,7	45,2
Average Mover Moving Percentage	%	8	10	14	14	11	13	0	0	0

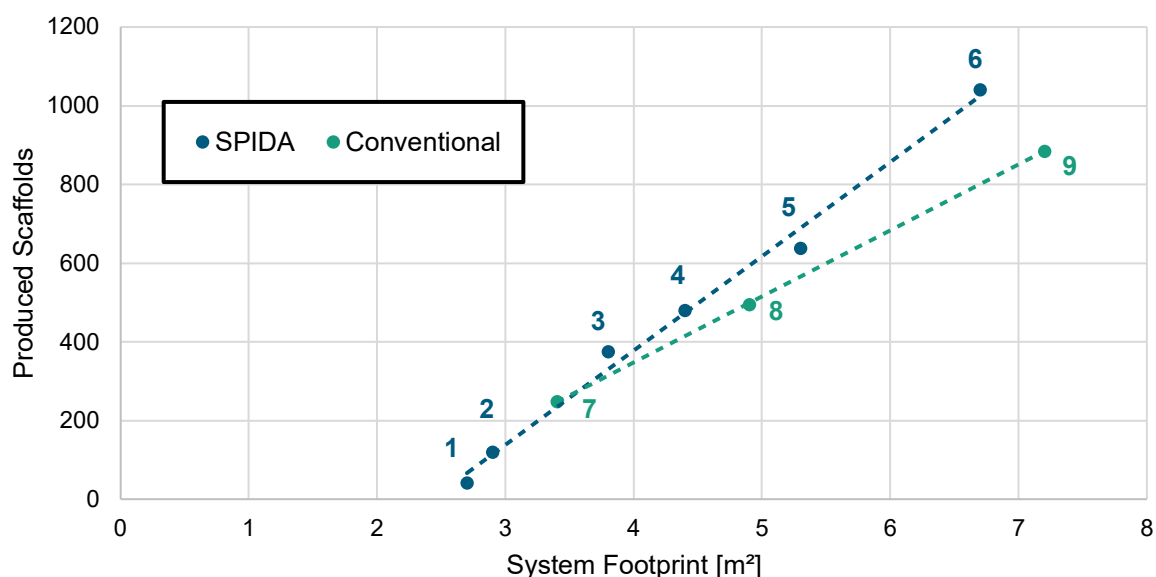


Figure 91: Comparison of the different production scenarios in terms of throughput and system footprint

Scenarios 7 to 8 show a steady increase in their production throughput. All footprint-independent parameters show comparable values, except for the Average "WaitForRobot" Time in Scenario 9. This value is 26,5 min, which is significantly lower than in Scenarios 7 and 8, which are each around 35 min. Comparing Scenarios 7 to 9 with Scenarios 1 to 6, it is noticeable that, the Average "Moving" Time is 0 in Scenarios 7 to 9, while this value is around 30 min on average in the other scenarios. At the same time, the average "WaitForRobot" and "Robotic-Transport" times are significantly higher in Scenarios 7 to 9, ranging from 21 to 36 minutes.

When comparing the two scenario classes in Figure 91, it is noticeable that the linearly regressed trend lines show a different gradient. The relative increase in production throughput

in relation to the system footprint is steeper for the SPIDA approach (Scenarios 1 to 6), than for the conventionally automated approaches (Scenarios 7 to 9).

Interpretation of Results

The reduced Average “WaitForRobot” Time in Scenario 9 compared to Scenarios 7 and 8 can be explained by the reduced Mover-Extruder ratio. The Average “Moving” Time in Scenario 7 to 9 is, as expected, 0, since no movers are used in these scenarios. On the other hand, the average “WaitForRobot” and “RoboticTransport” times are significantly longer in these scenarios than in Scenarios 1 to 6, since the robots perform all intralogistic transport steps and not just the application and separation steps at the storage locations.

The conventional approach in Scenarios 7 to 9 results in significantly lower extruder utilization because only one mover serves one extruder. For small layout configurations with fewer than seven extruders, a comparatively high throughput can be achieved in relation to the required footprint. This can be seen at the intersection of the trend lines in Figure 91. This indicates that with a configuration with an available space of about 3,5 m², approximately the same number of scaffolds can be produced with both production approaches. With a larger footprint, the trend lines diverge and the SPIDA approach achieves higher throughputs.

Accordingly, the hypothesis that SPIDA requires less space and less equipment than a conventionally automated production system to achieve the same production throughput can only be confirmed with limitations. On the one hand, only three scenarios for conventional production serve as a reference, which could possibly achieve higher throughputs with more in-depth optimization. On the other hand, it is shown that the advantage of the SPIDA approach tends to be more effective only in larger production plants with above 3,5 m² system footprint.

Interim Conclusion on Scalability Simulation Studies

With the validation results from this Chapter 5.3, the sub research question **SRQ4 “Can the digital production model be used for production planning regarding scalability and optimization?”**, can be answered affirmatively regarding scalability. Regarding optimization further studies are conducted in Chapter 5.4.

5.4 Optimization Simulations on a Digital Production Model

In this chapter, the DiSPIDA is used to simulate various optimization scenarios to confirm or refute defined hypotheses. Together with the results from Chapter 5.3, the sub research question SRQ4 can be answered, as visualized in Figure 92.

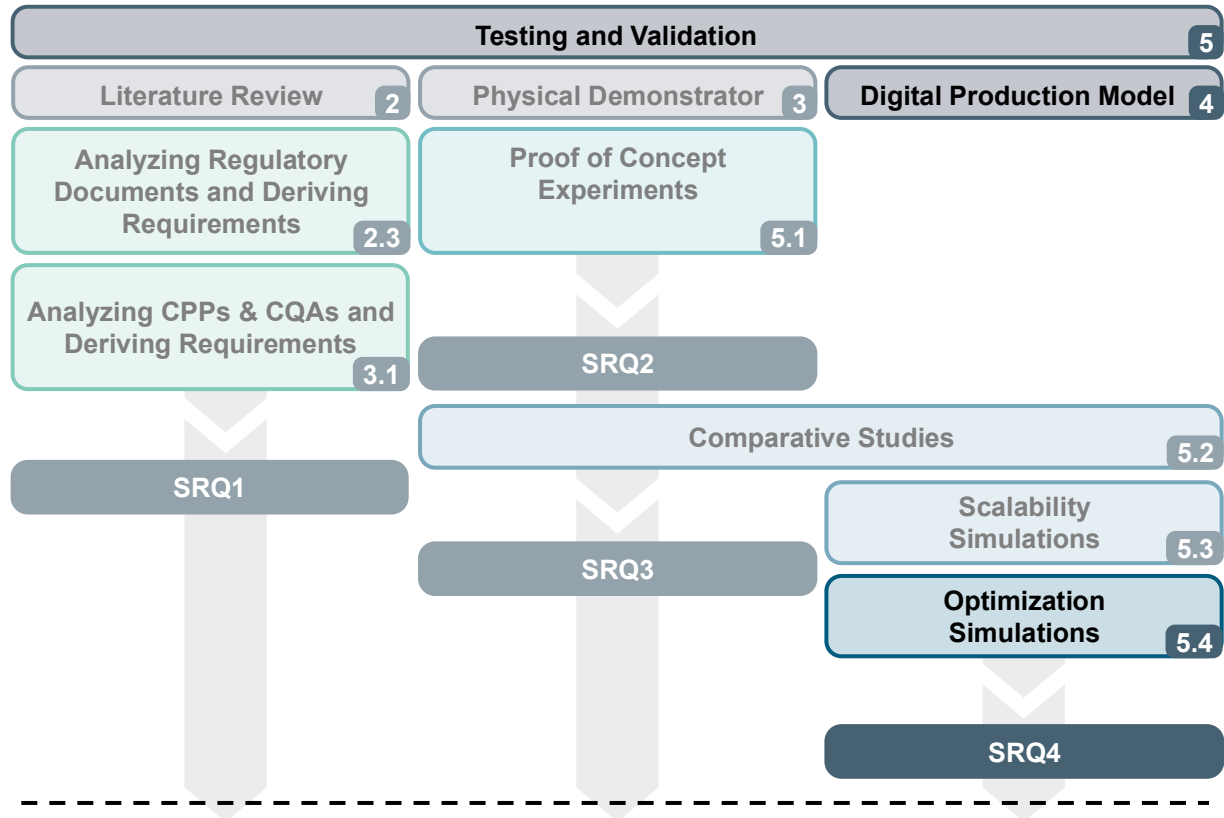


Figure 92: Segment of the testing and validation structure with focus on the scalability simulations with the digital production model

The DiSPIDA could be used to optimize production from several perspectives. These perspectives can relate to sustainable, economic or technical KPIs. For example, in the case of sustainability optimization, the production infrastructure can be designed in such a way that carbon dioxide emissions or electricity consumption are minimized. To do this, appropriate consumption databases would have to be linked to DiSPIDA. Another sustainability KPI (GreenKPI) would be material waste due to misprints, which could be optimized by adapting the QC strategy for example.

In terms of economic performance, SPIDA could be optimized to compare investment costs in relation to production throughput for different scenarios. Along with this, the duration until the return on investment is reached, can be predicted with corresponding simulations. This requires that assumptions are made for all material, investment and operating costs.

From a technical perspective, SPIDA can be optimized in terms of the optimal utilization of specific resources. This is useful, for example, if a specific cleanroom area is given on which the production throughput is to be maximized. Simulations with DiSPIDA can also be used for parametric optimizations. The design of the layout, the exact configuration of the positions and

quantities of movers and stations or the setting of parameters such as mover speed can be simulated for different scenarios and the effect on production throughput rates can be analyzed. The simulations with DiSPIDA can also be used to identify bottlenecks or logistical dead spaces.

In the context of this chapter, the optimization studies are focused on technical optimization. The utilization of DiSPIDA for economic optimization is discussed in the outlook in Chapter 7. In order to formulate hypotheses on how to optimize the production from a technical standpoint, an Ishikawa analysis is carried out (Ishikawa, 1996). A reduction in production throughput is defined as the problem. Since the developed digital model functions within a defined framework, an overall consideration of all 6M cause categories (man, machine, material, method, milieu, measurement) is not necessary. Instead, the machine and method strands are combined and broken down into the branches of layout, dynamics, settings and resources. Figure 93 shows the results of the Ishikawa analysis. In the following, the cause categories are briefly described:

- **Layout:** Reasons that can be traced back to impractical positioning of stations and mover home positions or the general configuration of the layout
- **Dynamics:** Reasons influencing the path planning of the movers during the simulation
- **Settings:** Reasons concerning the settings of the individual stations
- **Resources:** Reasons traced back to a lack or surplus of available resources

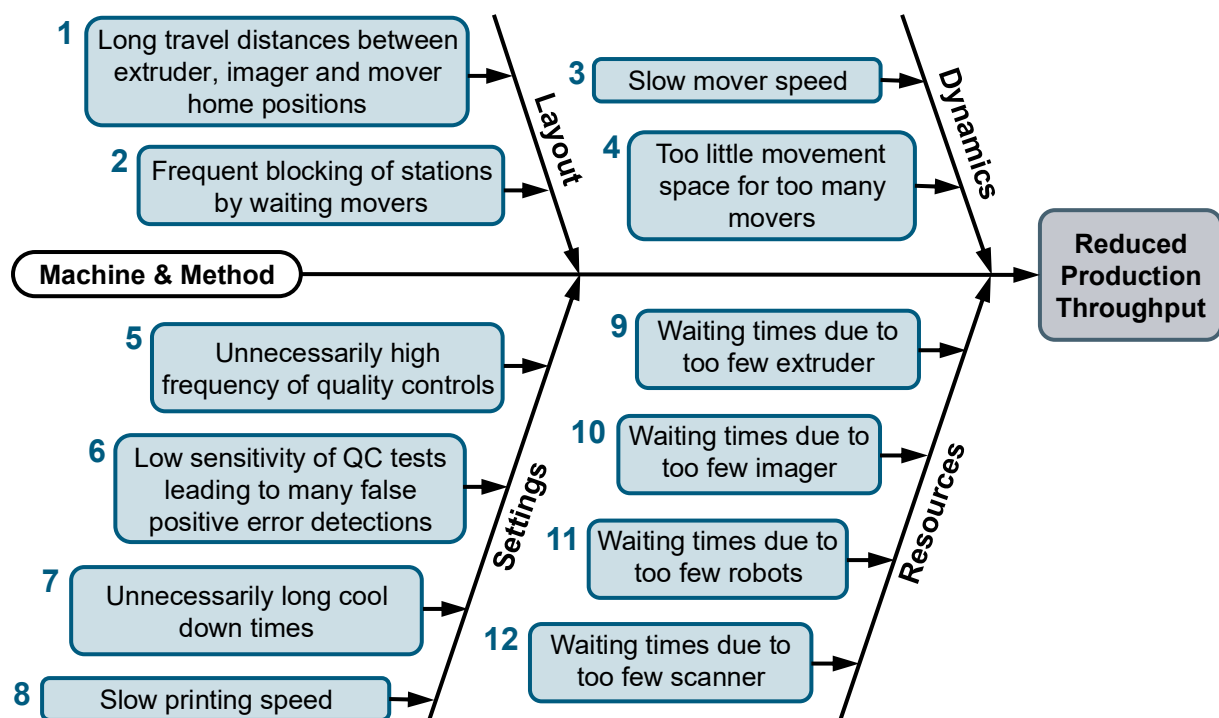


Figure 93: Ishikawa diagram showing causes that lead to a reduction in production throughput in the production model

Some of the reasons listed in the Ishikawa diagram, why a reduction in production throughput can occur, are trivial and are neglected for this study. Hypotheses are formulated based on reasons 2, 3 and 4 from Figure 93.

5.4.1 Layout Optimization

The following hypothesis is based on the qualitative observation that the positioning of the individual stations and the mover home positions have a significant influence on the productivity of the system.

Hypothesis 4

» Narrowly arranged stations lead to partially blocked stations by waiting movers, which results in decreasing throughput «

This hypothesis states that if extruders are positioned too close to each other, accessibility is affected because the extruders and the movers block each other when movers are trying to change positions. This then leads to more time-consuming paths for the movers and thus to a reduction in production throughput.

Test Scenarios and Model Preparation

To test the hypothesis, three production scenarios are implemented in DiSPIDA and the simulation results are compared. These three scenarios, which are shown in Figure 94, have the same number of stations and movers and have the same system footprint. The scenarios differ in the arrangement of their stations. Scenario 1 corresponds to Scenario 3 from Chapter 5.2.1 and has already been presented. For Scenario 2, this scenario was changed so that the extruders are concentrated at one corner of the system. In Scenario 3, the extruders were arranged next to each other along one side of the system and the movers were placed in front of them.

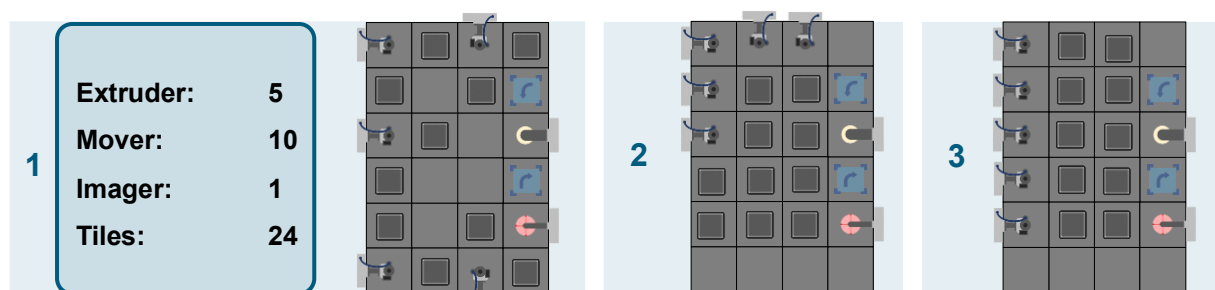


Figure 94: Comparison of scenarios with identical configuration but different arrangements of stations and movers

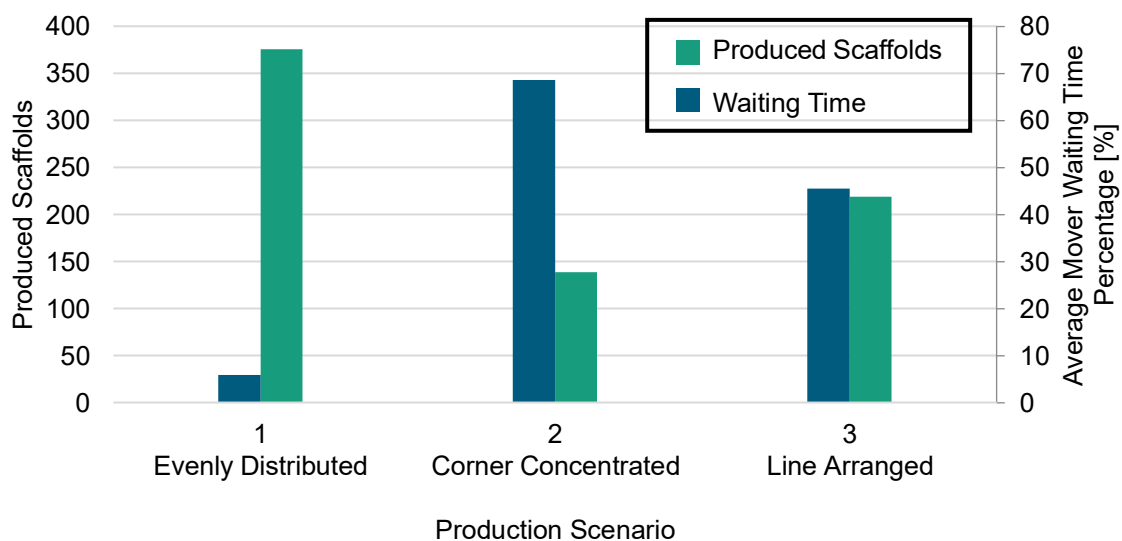
As in all investigations before, all other process parameters were kept consistent for all scenarios and five replications of the simulation were carried out.

Simulation and Data Collection

Table 24 shows selected data recorded from the simulations of the three production scenarios, whose configuration is shown in Figure 94. The focus of these results is on the values for produced scaffolds, extruder utilization and the average state times. Figure 95 highlights the values for production throughput and the waiting times of the movers.

Table 24: Simulation data for different production scenarios comparing different station arrangements

Production Scenario	Unit	1	2	3
Produced Scaffolds	1	376,0	138,6	219,0
Defect Scaffolds	1	36,6	15,2	21,8
System Footprint	m ²	3,8	3,8	3,8
Production Throuput per Area	1/m ²	98,9	36,5	57,6
Number of Active Extruders	1	5,0	5,0	5,0
Number of Tiles	1	24,0	24,0	24,0
Number of Active Movers	1	10,0	10,0	10,0
Number of Active Imagers	1	1,0	1,0	1,0
Number of Active Scanners	1	1,0	1,0	1,0
Average Total Production Time	min	215,6	562,4	365,0
Average "Printing" Time	min	88,0	88,3	87,5
Average "Scanning" Time	min	0,3	0,3	0,3
Average "Imaging" Time	min	9,2	9,2	9,1
Average "Moving" Time	min	30,1	3,6	26,6
Average "WaitForExtruder" Time	min	8,6	358,6	151,2
Average "WaitForScanner" Time	min	0,0	0,0	0,0
Average "WaitForImager" Time	min	3,9	27,0	14,8
Average "WaitForRobot" Time	min	0,3	0,3	0,3
Average "RoboticTransport" Time	min	0,2	0,2	0,2
Total Printing Time	d	5,0	1,9	2,9
Extruder Utilization Percentage	%	84,1	31,4	48,8
Average Mover Waiting Percentage	%	6,0	68,6	45,6
Average Mover Moving Percentage	%	14,0	0,6	7,3

**Figure 95: Comparison of different scenarios in terms of production throughput and average mover waiting time percentage**

When comparing the three scenarios, it is noticeable that Scenarios 2 and 3 produce significantly less. In Scenario 1, 376 scaffolds are produced. In Scenario 2, only 138,6 on average, and in Scenario 3, 219 scaffolds. At the same time, the average “WaitForExtruder” and “WaitForImager” times are significantly longer in Scenarios 2 and 3. This is also reflected in the extruder utilization percentage.

Interpretation of Results

The significant reduction in throughput in Scenarios 2 and 3 is caused by the significant increase in waiting times. In Scenario 2, the movers spend almost 70 % of their time waiting for a station to become free or for another mover to move on another tile. This can only be caused by the different arrangement of the stations, since all other parameters remain identical. One example to explain this, is that in Scenario 2, the extruder in the upper left corner can only be reached if one of the two adjacent extruders is not in use. Since this is rarely the case, the mover's accessibility and thus the system's productivity are severely limited. In Scenario 3, this effect is less pronounced because no extruder in a corner is enclosed by two other extruders. Nevertheless, four out of five extruders are only accessible from one side, which also means that this access is regularly blocked by other movers, and productivity drops. In Scenario 1, all extruders are always accessible from at least two sides, which reduces the complexity of the mover paths for position changes and thus increases productivity.

The hypothesis that narrowly arranged stations lead to partially blocked stations by waiting movers which results in decreasing throughput, can be clearly confirmed. This observation can also depend on the specific use case but should always be considered when planning the production layout. The DiSPIDA model can be used to identify these issues and to investigate and plan alternative layouts.

5.4.2 Dynamics Optimization

The following hypothesis is based on the qualitative observation that the movers transportation routes slow down the production process and increasing the movers speed lead to increased productivity.

Hypothesis 5

» Increasing mover speed increases production throughput «

The hypothesis states that a higher throughput can generally be achieved by increasing the transportation speed of the movers.

Test Scenarios and Model Preparation

This hypothesis is examined on the basis of two scenarios, which are shown in Figure 96. Both scenarios are parameterized with five values for the mover travel speed. The speed is doubled in steps between 0,125 m/s and 2 m/s. Although the simulation allows infinitely high values to be set, no further values are tested because the Beckhoff XPlanar™ system selected for the system concept only allows a maximum mover speed of 2 m/s. The different parameterizations of the two scenarios result in each five sub-scenarios 1.1 to 1.5 and 2.1 to 2.5.

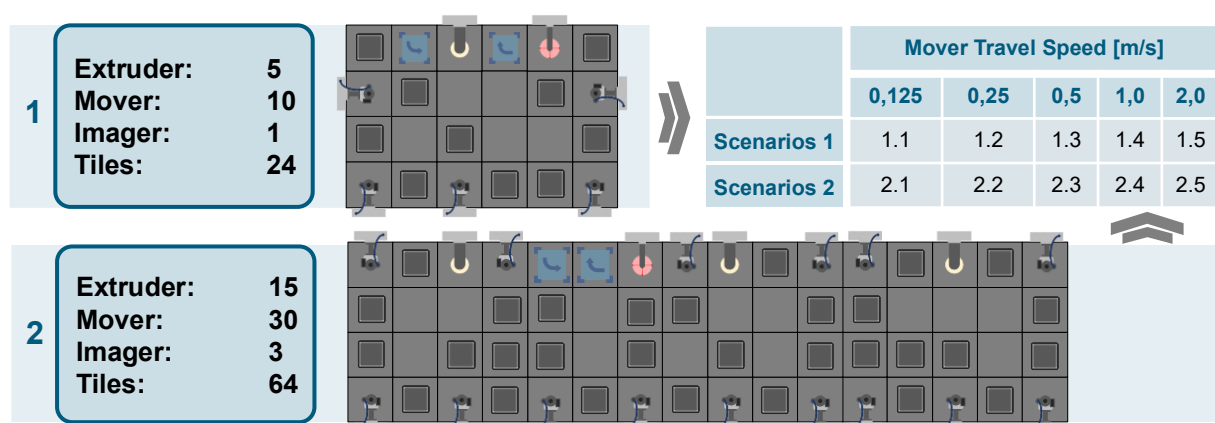


Figure 96: Illustration of the configurations used for testing different mover speeds

For the simulation of each sub-scenario, 5 replicates were carried out and the mean values and standard deviations are shown respectively in the following.

Simulation and Data Collection

Table 25 shows the simulation results for all sub-scenarios for the smaller production Scenario 1 and

Table 26 shows the results for all sub-scenarios for the larger production Scenario 2. It can be observed that the number of scaffolds produced is steadily increasing, but with a decreasing gradient. Taking into account the standard deviations, there is no notable difference between sub-scenarios 1.4 and 1.5. The extruder utilization percentage also increases steadily, with scenarios 1.2 to 1.5 having no significant difference. The same trends can be observed in scenario 2, although there is no continuous increase in the values. Figure 97 visualizes these observations in terms of production throughput. It also indicates whether there is a significant

difference between the sub-scenario data sets. The asterisk (*) indicates a significance level of $p < 0,05$, meaning that the probability that the data points come from the same data set is less than 5 %, according to an independent t-test.

Table 25: Simulation data for comparing different mover speeds within one production scenario

Production Scenario 1	Unit	1.1	1.2	1.3	1.4	1.5
Produced Scaffolds Mean	1	347,4	376	391,8	399,2	400,6
Produced Scaffolds SD	1	3,61	7,31	6,65	3,27	4,93
Mover Travel Speed	m/s	0,125	0,250	0,500	1,000	2,000
System Footprint	m ²	3,8	3,8	3,8	3,8	3,8
Number of Active Extruders	1	5,0	5,0	5,0	5,0	5,0
Number of Tiles	1	44,0	44,0	44,0	44,0	44,0
Number of Active Movers	1	10,0	10,0	10,0	10,0	10,0
Number of Active Imagers	1	1,0	1,0	1,0	1,0	1,0
Number of Active Scanners	1	1,0	1,0	1,0	1,0	1,0
Average Total Production Time	min	233,4	215,6	207,2	203,1	201,8
Average "Printing" Time	min	88,0	88,0	87,8	87,9	88,0
Average "Scanning" Time	min	0,3	0,3	0,3	0,3	0,3
Average "Imaging" Time	min	9,1	9,2	9,1	9,1	9,2
Average "Moving" Time	min	42,3	30,1	24,2	21,2	20,1
Average "WaitForExtruder" Time	min	12,3	8,6	7,2	6,5	6,4
Average "WaitForScanner" Time	min	0,0	0,0	0,0	0,0	0,0
Average "WaitForImager" Time	min	6,0	3,9	3,1	2,6	2,4
Average "WaitForRobot" Time	min	0,3	0,3	0,3	0,3	0,3
Average "RoboticTransport" Time	min	0,2	0,2	0,2	0,2	0,2
Total Printing Time	d	4,6	5,0	5,2	5,3	5,4
Extruder Utilization Percentage	%	77,4	84,1	87,3	89,0	89,4
Average Mover Waiting Percentage	%	7,9	6,0	5,1	4,6	4,5
Average Mover Moving Percentage	%	18,1	14,0	11,7	10,4	10,0

Table 26: Simulation data for comparing different mover speeds within an alternative scenario

Production Scenario 2	Unit	2.1	2.2	2.3	2.4	2.5
Produced Scaffolds Mean	1	972,2	1041,8	1076,8	1082,2	1076,4
Produced Scaffolds SD	1	8,228	8,5	12,9	10,4	9,2
Mover Travel Speed	m/s	0,125	0,25	0,5	1,0	2,0
System Footprint	m ²	6,7	6,7	6,7	6,7	6,7
Number of Active Extruders	1	15,0	15,0	15,0	15,0	15,0
Number of Tiles	1	64,0	64,0	64,0	64,0	64,0
Number of Active Movers	1	30,0	30,0	30,0	30,0	30,0
Number of Active Imagers	1	3,0	3,0	3,0	3,0	3,0
Number of Active Scanners	1	1,0	1,0	1,0	1,0	1,0

Average Total Production Time	min	249,9	232,7	225,8	249,9	225,4
Average "Printing" Time	min	88,0	88,1	88,2	88,0	88,1
Average "Scanning" Time	min	0,3	0,3	0,3	0,3	0,3
Average "Imaging" Time	min	9,2	9,2	9,2	9,2	9,2
Average "Moving" Time	min	40,8	30,8	25,3	40,8	20,4
Average "WaitForExtruder" Time	min	23,6	18,4	16,8	23,6	17,2
Average "WaitForScanner" Time	min	0,7	0,7	0,7	0,7	0,9
Average "WaitForImager" Time	min	11,7	9,7	9,8	11,7	13,9
Average "WaitForRobot" Time	min	0,3	0,3	0,3	0,3	0,3
Average "RoboticTransport" Time	min	0,2	0,2	0,2	0,2	0,2
Total Printing Time	d	4,3	4,6	4,8	4,3	4,8
Extruder Utilization Percentage	%	72,1	77,4	80,1	72,1	79,9
Average Mover Waiting Percentage %		14,6	12,5	12,2	14,6	14,3
Average Mover Moving Percentage %		16,3	13,2	11,2	16,3	9,0

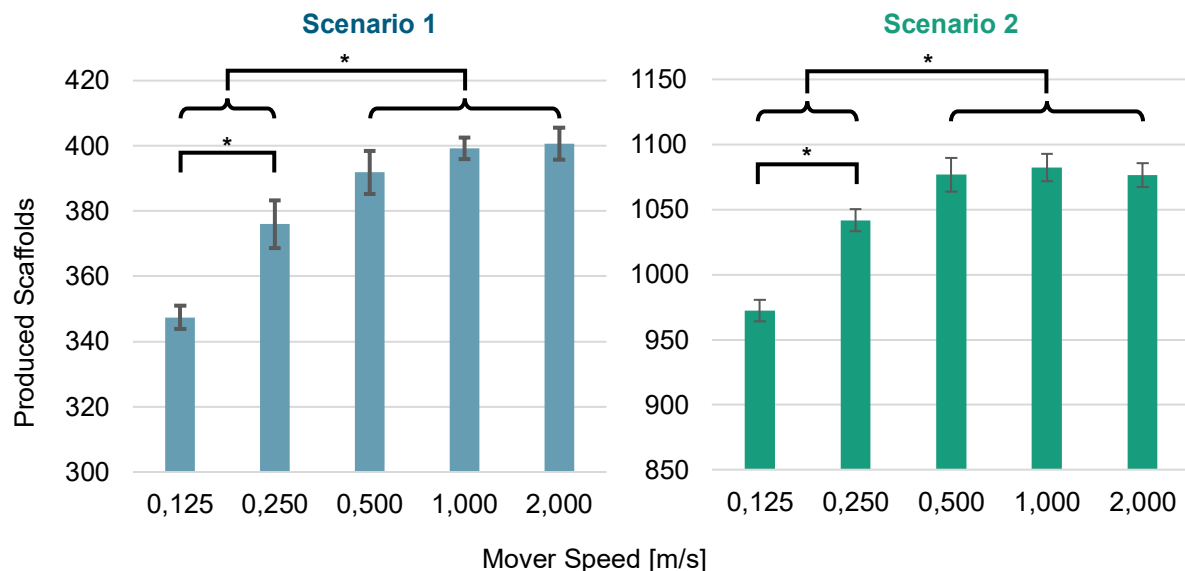


Figure 97: Produced scaffolds in relation to the mover transport speed used for two different production scenarios

In both scenarios, it is noticeable that from a speed of 0,5 m/s, a doubling of the mover speed to 1 m/s and to 2 m/s does not result in a significant increase in productivity.

Interpretation of Results

Based on the recorded data for both scenarios, the hypothesis that increasing mover transportation speed increases production throughput, can be partially refuted. This can be explained by the fact that the majority of production time is characterized by printing time itself and by waiting times, and not by the movers' transport times. Thus, when the speed increases, productivity must ultimately approach a limit. Due to the fluctuations in production throughput caused by the individualized products, the standard deviations will at some point exceed the further increase in productivity, so that a continuous increase can no longer be assumed.

Hypothesis 6

» Increasing the number of movers on a fixed space does not directly increase throughput «

This hypothesis states that it cannot be guaranteed that maximizing the number of movers while keeping the number of extruders constant will also maximize throughput.

Test Scenarios and Model Preparation

To test the hypothesis, the scenarios shown in Figure 98 were implemented in DiSPIDA. The only difference between the seven scenarios is that the number of active movers was increased in each successive scenario. Simulations were then carried out and the influences examined.

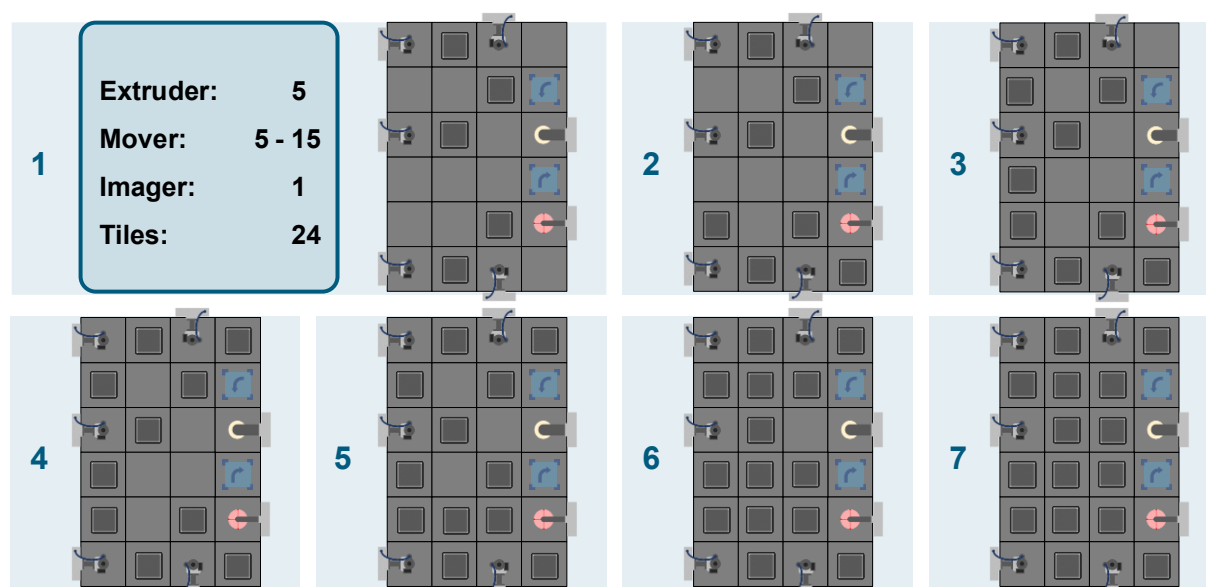


Figure 98: Comparison of scenarios with identical configuration but different amounts of active movers

Simulation and Data Collection

Table 27 contains the simulation results from the seven shown scenarios. The focus here is on the values regarding the Produced Scaffolds and the Number of Active Movers. The other recorded values can be used to interpret the results. Figure 99 supplements this data and illustrates the influencing factors.

It is noticeable that in terms of production throughput, a peak of 376 scaffolds is reached when ten movers are active on the system. With one mover less, the throughput is only 347 scaffolds; with one mover more, the throughput is 369 scaffolds. In each case, productivity decreases steadily before and after this peak. In this scenario, the ratio between movers and extruders is 2:1 and the open space-mover ratio is 1:2, or 50 %.

Table 27: Simulation results for different production scenarios for comparing the effect of different amounts of active movers.

Production Scenario	Unit	1	2	3	4	5	6	7
Produced Scaffolds	1	217	284	347	376	362	336	314
Defect Scaffolds	1	22	28	33	37	35	32	30
Number of Active Extruders	1	5,0	5,0	5,0	5,0	5,0	5,0	5,0
Number of Tiles	1	24,0	24,0	24,0	24,0	24,0	24,0	24,0
Number of Active Movers	1	5,0	7,0	9,0	10,0	12,0	14,0	15,0
Number of Active Imagers	1	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Number of Active Scanners	1	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Average Total Production Time	min	187	199	210	216	269	336	382
Average "Printing" Time	min	87,8	87,5	87,8	88,0	87,8	87,6	87,5
Average "Scanning" Time	min	0,3	0,3	0,3	0,3	0,3	0,3	0,3
Average "Imaging" Time	min	9,1	9,1	9,1	9,2	9,1	9,1	9,1
Average "Moving" Time	min	12,7	21,7	28,2	30,1	43,2	48,9	48,4
Average "WaitForExtruder" Time	min	1,1	3,6	6,1	8,6	46,2	101,9	142,5
Average "WaitForScanner" Time	min	0,0	0,0	0,0	0,0	0,0	0,1	0,1
Average "WaitForImager" Time	min	1,0	1,8	3,0	3,9	6,9	12,2	19,0
Average "WaitForRobot" Time	min	0,3	0,3	0,3	0,3	0,3	0,3	0,3
Average "RoboticTransport" Time	min	0,2	0,2	0,2	0,2	0,2	0,2	0,2
Total Printing Time	d	2,9	3,8	4,6	5,0	4,8	4,5	4,2
Extruder Utilization Percentage	%	48,4	63,3	77,3	84,1	80,6	74,6	69,6
Average Mover Waiting Percentage	%	1,3	2,9	4,5	6,0	19,8	34,1	42,3
Average Mover Moving Percentage	%	6,8	10,9	13,4	14,0	16,1	14,6	12,7

The extruder utilization also reaches its peak at 84,1 % with 10 active movers. The percentage of time that the movers spend waiting per scaffold increases steadily up to the 15th mover and reaches a value of 42,3 %. The percentage of time that the movers spend moving reaches its peak at 12 active movers with 16,1 %.

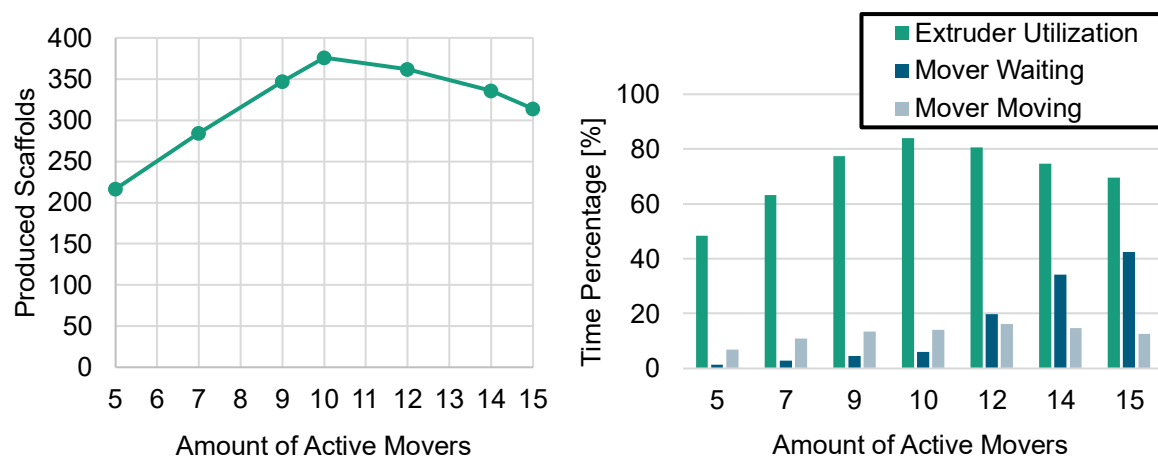


Figure 99: Visualization of the influence of the number of movers on productivity of the system and on the percentage of waiting time, movement time and extruder utilization

Interpretation of Results

Since the average “WaitForExtruder” time of 5 to 10 movers only increases slightly and more than fifefold increases from 10 to 12 movers, it can be interpreted that a turning point is reached in the range between 10 and 12 movers, where a higher mover-extruder ratio no longer contributes to an increase in productivity, because the simultaneously decreasing open space-mover ratio slows down the intralogistics processes more. The numbers of scaffolds produced, can be interpreted that this specific configuration reaches its peak at 10 or 11 movers. The ideal mover-extruder ratio is therefore approximately 2 movers per extruder.

The hypothesis that maximizing the movers on a system does not lead to maximizing the throughput, can be confirmed. The same reasons apply here as for the previous hypothesis. If there are too many movers active on a limited space, they block each other when changing position, which ultimately leads to longer waiting times and lower productivity. To perform a layout optimization, the ideal mover-extruder ratio must therefore be determined for each configuration. The DiSPIDA model can be used to determine the ideal number of movers required to achieve the highest possible production throughput with the fewest possible resources, for individual use cases.

Interim Conclusion on Optimization Simulation Studies

With the validation results from this Chapter 5.4 and the previous Chapter 5.3, the sub research question **SRQ4 “Can the digital production model be used for production planning regarding scalability and optimization?”**, can be answered affirmatively in all respects.

5.5 Validation Conclusion

Based on the validation definition according to DIN EN ISO 9001:2015 and the IEEE, the extent to which the developed production concept satisfies the specified requirements was examined. The affirmative answer to the main research question, which is based on the requirements, implies the fulfillment of these requirements, as visualized in Figure 100.

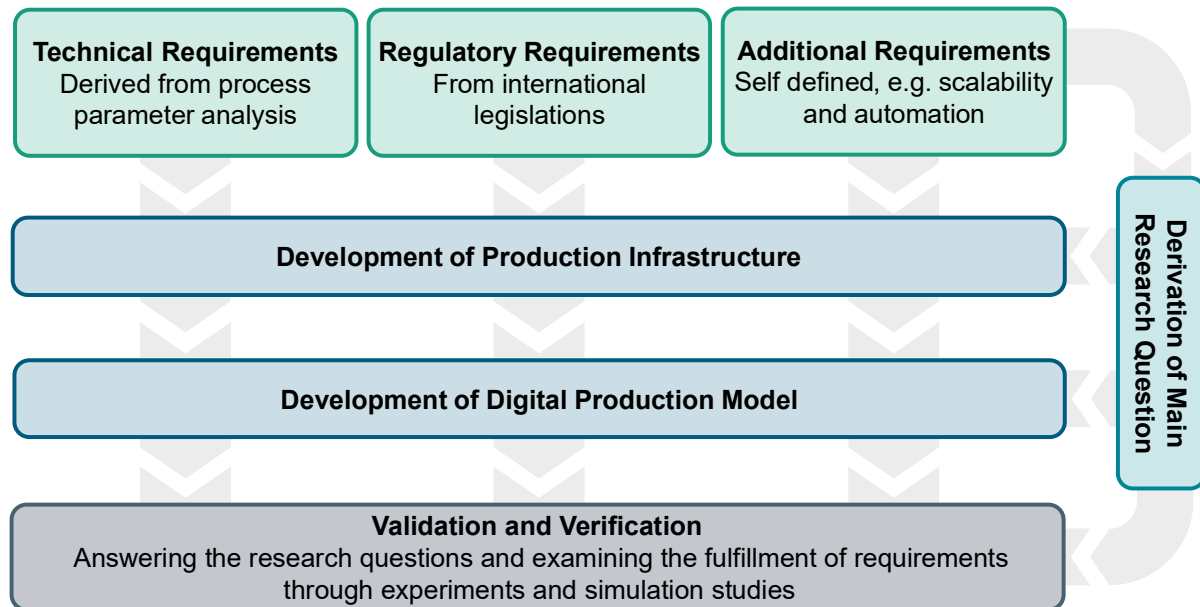


Figure 100: Visualization of the relationship between the main research question and the fulfillment of the requirements for validation

Within this chapter, the results of PoP experiments are shown, which prove that the PEAM approach is suitable for 3D printing and for automating the process chain. To enable holistic automation, it has also been shown that inline integration of quality control is possible for the production concept. This answers sub research question SRQ2. In addition, it was verified that the concept is suitable for decoupled production and thus favors parallelization approaches. The scalability of the production infrastructure was examined using a digital model. Its realistic representation of reality was shown in a comparative study, which ultimately answers the sub research question SRQ3. Different influences on the throughput scalability of the system were investigated and a comparison was drawn with conventional concepts. In addition, it was verified that the model can be used to optimize production. Therefore, sub research question SRQ4 is answered affirmatively. All sub research questions (SRQ1-SRQ4) have thus been answered and show in summary that EAM-based production of individual scaffolds can be realized in a holistically automated and scalable form.

The main research question **MRQ “Can extrusion-based additive manufacturing of personalized medical scaffolds be end-to-end automated for a scalable production?”** was thus conclusively and comprehensively answered with an affirmative.

Concluding the research process according to Ulrich, the step (E) is completed and the final step (G) of “Practice Consultancy” is initiated, compare Figure 5 (Ulrich and Hill, 1976).

6 Critical Discussion

In the following, critical aspects and limitations of this work are discussed. These include the initial collection of requirements, the subsequent concept development and modeling of the production infrastructure, as well as the concluding validation measures. The transferability of the results is evaluated within the outlook in Chapter 7.

Requirements Assessment

With regard to the regulatory framework for the manufacture of medical devices, all relevant legislation for Europe and USA has been screened comprehensively. However, this only reflects the current status of these regulations, which are regularly expanded and updated. Also, much of the legislation assumes that the current state of technology and knowledge is taken into account when planning production and designing processes, which is also constantly evolving. The derived overall requirements in terms of regulation are therefore only a temporary snapshot and must be carefully reconsidered for each new or changed use case. However, the methodology presented in this work regarding screening and harmonization of regulatory requirements can be used as a guideline.

The literature research regarding process parameters and quality attributes in extrusion-based 3D printing was carried out systematically but can also only provide a current snapshot and cannot guarantee completeness. However, due to the large number of available publications in the field of 3D printing and the broad consensus among them, it can be assumed that all relevant process parameters are identified for the use case considered. More specific additional aspects, for example, concerning the specific use of an FGF extruder system, which is less common in the state of the art, which also means that the literature is not quite as comprehensive and relevant process parameters could be omitted. Regarding the quality attributes of medical PCL scaffolds, it can be assumed, based on the large amount of literature, that all attributes have been identified and taken into account for the derivation of the technical requirements for quality assurance.

Production Concept Development

The development of the SPIDA concept was carried out according to standard methodologies established in engineering. However, since the research of individual solutions for the automation of individual process steps was carried out exploratively, it cannot be guaranteed that all possible technologies were considered and added to the morphological box. The compilation was carried out to the best of the author's knowledge and understanding. The evaluation of these collected solutions was substantiated on the basis of performance criteria. These criteria are qualitative and very general, which, although it allows a pairwise comparison of two technologies, does not allow a differentiated quantitative evaluation of technical parameters. A critical point to note is that the evaluation of the economic efforts is only qualitative and is not based on actual figures. As these are measures for the development of a concept, the technical elaboration of which is subject to later development stages. The iterative development approach also allows for decisions regarding individual technical approaches to be changed and

reworked afterwards. The qualitative decision-making methodology used is therefore proportionate and expedient, even if the completeness and optimality of the selected solutions cannot be guaranteed. To verify the chosen concept, a subsequent expert survey could have improved the quality of the decision, since the evaluations using the performance criteria would not have depended solely on the knowledge and understanding of the author, rather a broader expertise would have been consulted. For this expert survey, it would have been necessary to interview specialists from the fields of automation technology, mechanical and plant engineering, electrical engineering, medical technology and software development in order to map all competencies holistically and to be able to make a more valid concept selection.

When validating the selected concept, the focus is only on three core components that represent the highest degree of innovation and cannot be verified by referencing the state of the art. This has the disadvantage that the automation of the conceptualized production infrastructure has not been practically validated in a holistic approach and thus there is a residual risk that technical hurdles have been overseen. Since this work has a clear focus on conducting research and exploring new approaches and not on integrating established technologies into new applications, the method of focusing on the innovative aspects of PEAM, integrated QC and a scalable MAPF algorithm, is comprehensible but not comprehensive.

A critical point to be considered is that the implementation of automatic evaluations of the recorded image data of the scaffolds was not considered in detail during the development of the inline integration solution for quality control for PEAM. For holistic automation, it would be necessary for the identified QA to recognize corresponding features and for the system to react adaptively. Although such evaluations are already covered by the state of the art and can be integrated into this application concept via respective interfaces, it is not guaranteed that the inline approach would work seamlessly with PEAM, since processes such as automatic focusing or height positioning of the camera would also have to be implemented in order to focus the corresponding layer. In addition, only cuboid, uniform test scaffolds were used in the validation experiments. With more uneven, personalized scaffold geometries, the automatic evaluation of image data is further complicated.

Digital Model Development

The development of the DiSPIDA production model was carried out systematically using established guidelines. In addition, the comparative studies between the digital model and the physical demonstrator have convincingly shown that the model realistically reflects the demonstrator's motion sequences. Nevertheless, the limitations of the digital model, which restrict the significance of the results, must be critically considered.

The model is limited in the way that it only simulates the motion paths and the process times for the purpose of simulating the logistics of the production infrastructure. Relevant aspects such as the extrusion process are not summarized in the sense that the material application and the occurrence of specific errors are modeled. Only the time required for this is modeled and an error rate can be configured. The model is also limited in terms of simulating motion sequences, since the current implementation only allows movements at a constant speed and does not take into account the acceleration and deceleration of the movers, which, can have

an impact on process times, especially on large-scale platforms. In principle, it is possible to implement the accelerations in JaamSim, but this requires further development.

One critical aspect is that the MAPF solver was implemented directly into the process structure in JaamSim, and not via an interface to another environment, for example, Python, where different algorithms could be tested in a modular way and more extensive mathematical operators would be available. Generally, the lack of comparison of different MAPF algorithms to solve the mover coordination problem can be criticized.

A final point of criticism concerns the validation with the demonstrator as a reference. Even if the demonstrator can serve as a physical prototype for small models, it is questionable whether a scaled model can then be perceived as a realistic representation of a large-scale production.

Experiments and Simulation Studies

The experimental validation of the PEAM approach is limited to a PoP, which was successfully provided. A proof that the PEAM approach achieves comparably good results as established EAM systems is still pending and was outside of the scope of this work. This would require comprehensive parameter studies. As already mentioned, the validation of the quality assurance concept is limited to the exemplary integration of an imaging system. Thus, no complete quality assurance is tested on the system but would be mandatory for transfer to industrial applications. In addition to the imaging system, test implementations of a weighing cell and a laser profile sensor were carried out, but their performance was not examined in detail.

Regarding the investigation of the dynamically interconnected AM approaches on the demonstrator system, it is critical to note that although multiple agents were used, for example, multiple extruders were not used, so that a flexible selection of the same resources could not be tested. This was investigated with the digital model but not on the demonstrator system due to a lack of available hardware.

The comparative studies between demonstrator and model are limited by the fact that only motion sequences and process times are compared. A comparison of the extrusion behavior and the quality of the produced products is not considered. In the case of the scalability studies, only selected representative scenarios can be compared with each other in order to refute or confirm hypotheses due to the unlimited possibilities in the design of the layout with the model. General rules cannot be derived using this approach. Since the scope of the work is to show that the DiSPIDA model can be used to plan production scaling and not to derive an optimally scaled production, the measures carried out are justifiable.

This also applies to the optimization studies, although here the focus is exclusively on the optimizability of technical parameters regarding layout and dynamics. Also, only isolated scenario comparisons are carried out. This limits the informative value of the results, due to the strict use case dependence, but is sufficient to demonstrate that the methodology can be used for optimization. Using the model for economic and ecological optimizations is technically possible but is considered to be a subject for future research.

7 Summary and Outlook

Summary

Personalized medical devices are becoming increasingly important, particularly in the field of regenerative medicine. Of particular importance are bioresorbable scaffolds that are adapted to the individual geometries of the patients and are used for the reconstruction of tissues and organs. The established manufacturing technology for these three-dimensional scaffold structures is extrusion-based three-dimensional printing. However, the industrialization of this technology has only progressed to a limited extent. The state of the art shows that many essential process steps, such as parameterization of the printer, material handling, print monitoring, inspection of the finished products and its quality assessment, are carried out manually. These approaches are difficult to scale and limit the efficiency of the production. Since the entire production process must take place in a controlled cleanroom environment, the human as part of the production line, poses a risk factor for errors, which further emphasizes the benefits of an automated solution. The design of a corresponding production infrastructure for the extrusion-based manufacturing of personalized scaffolds was identified as a research gap and is the central objective of this work. The topic is investigated conceptually and by utilizing physical demonstration systems and digital models.

The central result of the work is a concept for a novel scalable production infrastructure based on a magnetic planar drive. This planar drive is used for production intralogistics and enables a multi-agent approach for flexibilization and simultaneous processing of multiple print jobs in the sense of decoupled production. On the other hand, the individual agents of the planar drive, the so-called movers, are used as printing beds and horizontal kinematics for 3D printing, so that the printing processes of the individual layers, the production intralogistics and other process steps, such as quality control, can be seamlessly connected.

The core innovations of the developed concept are therefore the utilization of the planar drive for extrusion additive manufacturing, the implementation of a scalable multi-agent path finding algorithms for decoupled production and the inline integration of quality control mechanisms. To validate these approaches, a physical demonstrator was developed that provides experimental proofs of principle for the three approaches. At the same time, a digital representation of the production infrastructure was modeled and implemented in a discrete-event simulation environment. It was shown that the digital model can realistically replicate the process flows of the physical demonstrator. Furthermore, simulation studies demonstrated that the model can be used to plan production scaling. It was also shown that the model can be used to optimize production processes. These optimizations concern, for example, the design of the layout of the production platform, including the arrangement of individual stations, or the optimization of technical parameters such as processing and transportation speeds.

Ultimately, the main research question, which asks whether extrusion-based additive manufacturing of personalized medical scaffolds can be end-to-end automated for scalable production, was answered affirmatively.

The investigations show that the developed concept is not only suitable for scaling the production of personalized medical scaffolds, but also offers the potential to be transferred to other applications in biomedical production. Individual approaches, such as the algorithms for scalable multi-agent path planning, can also be used across different domains for other applications and contribute to the advancement of the state of the art in the field of decoupled production.

Outlook

The developments and findings of this work offer opportunities for future research in the field of production technology for personalized medical scaffolds. These aspects, as well as the transferability to related applications, are presented in the following.

Parameter Studies to Improve PEAM Print Quality

Since only a general feasibility has been demonstrated for the PEAM approach, this work can now be continued by conducting systematic and detailed parameter studies with regard to this printing technology. In this context, it is recommended that the levitation height of the movers during the extrusion process and the deposition speed in particular be examined more closely, since these parameters are determined by the magnetic planar drive and influence the precision of the kinematics and thus the quality of the print. There are no published studies on this in the literature, so there is an existent research gap.

Elaboration and Validation of the Quality Management System

For quality assurance of the printed scaffolds, a corresponding QMS was conceptualized on a high level. The necessary measurement technology was integrated using an imaging system as an example. To professionalize the overall concept, it is imperative that the automatic quality assurance is further developed and also validated in terms of data evaluation. To this end, further research and development is needed in the field of image evaluation of recorded scaffold layers. It is also recommended to take a closer look at other measurement techniques to assess the quality attributes of a scaffold. These are listed in the morphological box in Chapter 3.2. For example, optical coherence tomography could be used for non-invasive control of interlayer bonding and possibly achieve better results than simple image evaluation. Also, the compliant processing of all data at an organizational level needs to be explored in further detail.

Expansion of the Digital Model for Economic and Ecological Assessments

The developed DiSPIDA model has the potential to be used for ecological and economic investigations of the production if it is expanded accordingly. With regard to economic aspects, investment costs and operating costs would have to be assigned to each device, i.e. mover, extruder, tile, etc. With additional information on the printing material costs and general operating costs of the cleanroom, the fixed and running costs of the production can then be automatically simulated and balanced against the income from the completed scaffolds. This means that economic efficiency can also be included as an optimization factor when planning new production layouts or configurations.

The model can be similarly modified with regard to the ecological assessment of the production. Therefore, for example, data regarding the electricity consumption of the entire infrastructure, as well as data on the carbon footprint, must be assigned in order to simulate its development for different production scenarios. This data can then be taken into account for production planning. The implementation of these measures does not pose a major technical hurdle. However, collecting reliable data can be difficult. Even though the degree of innovation is not particularly high for this model expansion, the DiSPIDA model's potential for dissemination in the private sector increases.

Transferability to Other Applications

The SPIDA concept was developed specifically for the use case of producing personalized medical scaffolds, so its advantages are designed for this application specifically. However, the following aspects can also be used for other applications. Aside from PCL-based scaffolds, applications in the field of bioprinting are also conceivable for these production systems. Instead of printing molten polymers, the system could be further developed to process cell-laden hydrogels by utilizing different extruders and adding stations for incubation.

Without the 3D printing component, approaches of the concept can be used for other production applications. For example, the planar drive-based production intralogistics could also be applied to use cases in the area of cell therapy manufacturing, where cultivation vessels or closed bags are transported free-chained to the required station depending on the required process step. In this application, the personalization of the product is also prevalent, and the biological variability brings the advantages of decoupled production to bear.

In principle, the system can also be used for applications outside the biomedical context. However, the advantages such as good cleanroom compatibility are then of less importance, so that from a techno-economic point of view, more classic automation approaches can be equally efficient. One aspect that can be relevant in many different areas are scalable MAPF solvers for decoupled production. Such approaches are gaining in importance in assembly and logistics. This work has shown that flexible, decoupled processes also offer advantages for other applications such as extrusion-based additive manufacturing and that this topic still holds potential for improvement in future production technology research.

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III Table of Symbols and Abbreviations

Abbreviation	Description
3D	Three-dimensional
AL	Alginate
AL-GE	Alginate-Gelatin
AM	Additive Manufacturing
AOET	Actual Order Execution Time
APT	Actual Production Time
AUBT	Actual Unit Busy Time
B-Event	Booked Event
BC	Biocompatibility
BD	Biodegradability
C-Event	Conditional Event
CAD	Computer-Aided Design
CBS	Conflict-based Search
CFU	Colony-forming Units
CGMP	Current Good Manufacturing Practice
CNC	Computer Numeric Control
COPE	Control Operate Plan Execute
CPP	Critical Process Parameter
CQA	Critical Quality Attribute
CT	Computed Tomography
DES	Discrete-event Simulation
DHR	Device History Record
DIAMS	Dynamically Interconnected Additive Manufacturing System
DIAS	Dynamically Interconnected Assembly Systems
DiSPIDA	Digital Model of SPIDA
DMR	Device Master Record
EAM	Extrusion Additive Manufacturing
ERP	Enterprise Resource Planning

EU	European Union
FDA	Food and Drug Administration
FDM®	Fused Deposition Modeling
FFF	Fused Filament Fabrication
FGF	Fused Granulate Fabrication
FIFO	First-In-First-Out
FLM	Fused Layer Modeling
G-Code	Geometrical Code
GE-PEG	Gelatine-Polyethyleneglycol
FPY	First Pass Yield
GP	Good Parts
GQ	Good Quantity
HEPA	High Efficiency Particulate Air
ICBS	Improved CBS
ICTS	Increasing Cost Tree Search
IEEE	Institute of Electrical and Electronics Engineers
IP	Inspected Parts
IQC	Inline Quality Control
ISO	International Organization for Standardization
ISPE	International Society for Pharmaceutical Engineering
KPI	Key Performance Indicators
LIMS	Laboratory Information Management System
LSL	Lower Specification Limits
MAL	Material Airlocks
MAPF	Multi-agent Path Finding
MDR	Medical Device Regulation
MEX	Material Extrusion
MRI	Magnetic Resonance Imaging
MRQ	Main Research Question
MRT	Magnetic Resonance Tomography
NC	Numeric Control

OEE	Overall Equipment Effectiveness Index
PA12	Polyamid 12
PAL	Personnel Airlock
PBS	Priority-based Search
PBT	Planned Busy Time
PCL	Polycaprolactone
PEAM	Planar Drive-based EAM
PEEK	Poly-ether-ether-ketone
PEG	Polyethylene Glycol
PETG	Polyethyleneglycol-terephthalate
PLA	Polylactic Acid
PLC	Programmable Logic Controller
PLGA	Polylactic-co-glycolic Acid
PoP	Proof of Principle
PP	Process Parameters
PQ	Produced Quantity
PRI	Planned Runtime per Item
QA	Quality Attributes
QM	Quality Management
QMS	Quality Management System
QMSR	Quality Management System Regulation
QSR	Quality System Record
ROI	Return on Investment
RRT	Rapidly-exploring Random Tree Search
SE	Simulation Environment
SI	Silicone
SPIDA	Scalable Production Infrastructure for Dynamically Interconnected Multi-agent EAM
SRQ	Sub Research Question
TPU	Thermoplastic Polyurethane
ULPA	Ultra-Low Particulate Air

USA	United States of America
USL	Upper Specification Limits
VDI	Association of German Engineers
WHO	World Health Organization

Symbol	Unit	Description
C_p		Process Capability Index
C_{pK}		Critical Process Capability Index
$V_{Scaffold}$	mm ³	Volume of the enclosing scaffold geometry
$h_{Scaffold}$	mm	Height of the scaffold
$d_{Scaffold}$	mm	Diameter of the scaffold base
$V_{Material}$	mm ³	Volume of printed material
$h_{Scaffold,Mean}$	mm	Scaffold Height Mean
$h_{Scaffold,Min}$	mm	Scaffold Height Minimum
$h_{Scaffold,Max}$	mm	Scaffold Height Maximum
$h_{Scaffold,SD}$	mm	Scaffold Height Standard Deviation
$d_{Scaffold,Mean}$	mm	Scaffold Diameter Mean
$d_{Scaffold,Min}$	mm	Scaffold Diameter Minimum
$d_{Scaffold,Max}$	mm	Scaffold Diameter Maximum
$d_{Scaffold,SD}$	mm	Scaffold Diameter Standard Deviation
h_{Layer}	μm	Layer Height
$P_{Scaffold}$	%	Scaffold Porosity
$n_{Scaffold}$		Number of printing layers required for a scaffold
n		Number of an individual layer within the scaffold
d_n	mm	Diameter of an individual layer within the scaffold
V_n	mm ³	Volume of the slice of an individual layer within the scaffold
$V_{Material,n}$	mm ³	Volume of printed material for an individual layer within the scaffold
$t_{Print,n}$	s	Printing time required to complete an individual layer

$\dot{V}_{Print}$	mm ³ /s	Material extrusion rate of the printer
σ		Standard Deviation
$\emptyset$		Mean Value
d_{Nozzle}	mm	Nozzle Diameter
V'_{Ex}	ml/s	Extrusion Rate
v_{Mover}	m/s	Mover Deposition Speed
h_{Mover}	mm	Mover Levitation Height
T_{Nozzle}	°C	Extrusion Temperature
$T_{Ambient}$	°C	Ambient Temperature
$H_{Ambient}$	%	Ambient Humidity
t_{Cool}	s	Cool Down Time
$T_{Platform}$	°C	Platform Temperature
FP	m ²	System Footprint
T		Number of Tiles
E		Amount of Extruder
S		Amount of Scanner
I		Amount of Imager
P_{Area}	m ²	Area of peripheral systems
T_{Area}	m ²	Area of one Tile
Ac	μm	Dimensional Accuracy
P	g/cm ³	Porosity
LB	%	Layer Bonding

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VI Student Theses

The results presented in this thesis are partially based on data and findings obtained in student projects carried under the operational supervision of the author. Principal findings from the following theses have been incorporated into parts of this thesis:

- **Ece Umar, 2021**, Development of a Guideline for the Design of a Regulatory Compliant Production System for Medical Implants
- **Maximilian Scholz, 2023**, Software Development for Simulating a 3D Printing Process based on a Magnetic Planar Drive
- **Sven König, 2023**, Conceptualization of a Fully Automated 3D Printing System for Scalable Production of individualized Medical Products
- **Abd-Alsalam Housin, 2024**, Conflict-based Model Predictive Control for Collision Avoidance of Multi-agent Systems
- **Sofia Rivero Feidt, 2024**, Simulation of a Scalable Individual Production for Additively Manufactured Medical Devices
- **Manav Thakkar, 2024**, Proof of Concept for Magnetic Planar Drive powered Fused Deposition Modeling
- **Jannis Ole Sußdorf, 2025**, Development of a Quality Assurance Concept for the Automated Manufacturing of Custom-made Scaffold Implants
- **Revant Bhatt, 2025**, Characterization and Optimization of Process Parameters for Polycaprolactone-based Medical Scaffolds for a Magnetic Planar Drive-based 3D Printer

VII Annex

A.1 Literature Overview on EAM Applications

Supplementary to Figure 1, the following literature overview is provided for the individual product classes.

Number	Application Category	References
1	Orthoses for Corrective Treatments	(Kim et al., 2018; Portnova et al., 2018; Vennam et al., 2024)
2	Orthoses for Healing Protection	(Cha et al., 2017; Chen et al., 2017; Choo et al., 2020; Vennam et al., 2024)
3	Protheses	(Abbady et al., 2022; Kate et al., 2017; Kim et al., 2022; Vennam et al., 2024)
4	Soft Tissue Reconstruction Scaffolds	(Berkane et al., 2024; Kennedy et al., 2023; Visscher et al., 2017)
5	Hard Tissue Reconstruction Scaffolds	(Sun et al., 2022; Winarso et al., 2022; Zhang et al., 2019)
6-9	Cell-laden Biohybrid Implants	(Berkane et al., 2024; Xie et al., 2020)
10	Special Geometry Tools	(Frizziero et al., 2021; George et al., 2017)
11	Tool Guidance Parts	(Frizziero et al., 2021; George et al., 2017)

A.2 Questionnaire and Answers of the Industry Survey

The questionnaire was sent to 22 companies and completed by 4 companies. Three completed the questionnaire in full and one company partially.

Number	Question	Answer Option	Votes
1	Which category best describes your company's products?	a) Orthoses	0
		b) Protheses	1
		c) Implants	3
		d) Surgical Equipment	0
2	What is the degree of personalization of your medical device?	a) Each product is individually customized for each patient.	2
		b) We offer a wide range of off-the-shelf products to provide a suitable solution for every patient.	1
		c) We offer multiple off-the-shelf products, which fit for most patients.	1
		d) We offer a one-size-fits-all product.	0
3	What level of automation is most applicable to the production of your product (compare picture below)?	a) The 3D printing process (3) runs automatically, all other processes are carried out manually.	4
		b) Further processes, such as quality control, are automated.	0
		c) Almost all process steps are automated.	0
		d) The production is automated from end to end. The staff only has to provide material and remove finished products.	0
4	What level of digitalisation is most applicable to the production of your product?	a) We start our machines manually and document all data manually.	4
		b) We can control our machines remotely and monitor them online, as well as record process data continuously.	0
		c) We have implemented advanced tools for production orchestration, such as AI-based scheduling.	0
5	What is your current production throughput?	a) 1-10 products per week	1
		b) 10-50 products per week	1
		c) 50-100 products per week	1
		d) 100-500 products per week	0
		e) 500-1000 products per week	0
		f) 1000-5000 products per week	0

6	What is your optimistically aimed production throughput for the future (5-10 years)?	a) 1-10 products per week	0
		b) 10-50 products per week	1
		c) 50-100 products per week	0
		d) 100-500 products per week	1
		e) 500-1000 products per week	1
		f) 1000-5000 products per week	0
7	Which option best describes the scalability of your production?	a) We are scaling up our production by adding further 3D printing systems to operate in parallel. Our production throughput increases in linear proportion to the available production space and production machines.	2
		b) We are scaling up our production by adding further 3D printing systems to operate in parallel, but we can benefit from scale effects up to a certain throughput.	1
		c) We operate an integrated production system that can be expanded as needed. Our production throughput increases exponentially with the available production space and production machines.	0
8	What challenges are you currently facing, or will you face in the future with regard to your production?	a) We are encountering problems finding sufficiently qualified personnel for our production.	0
		b) We are not aware of any solutions for fully automated production that meet our requirements.	2
		c) We are having trouble finding machines that meet the regulations for medical device production.	1
		d) We lack the expertise to further digitalise/automate/scale our production.	0
		e) other	1

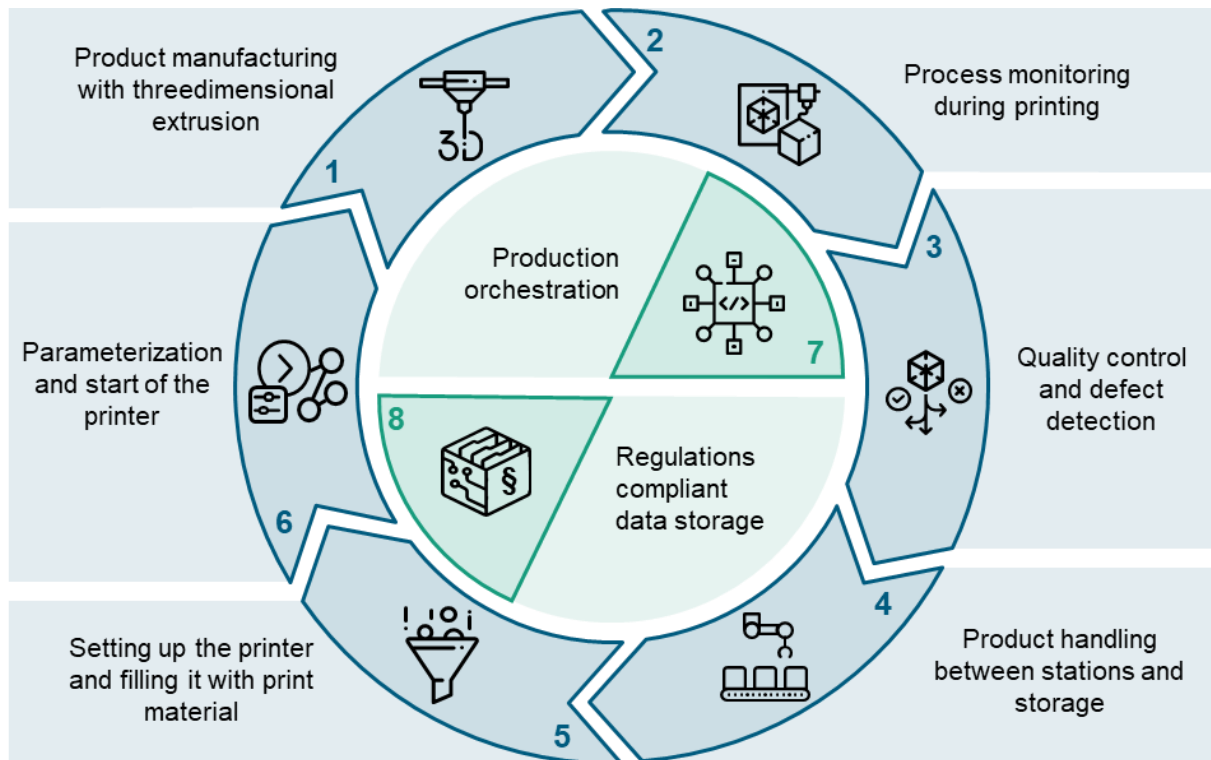


Figure A1: Attachment for Question 3

A.3 Literature Review on EAM PP and QA – Article Summary

Number	Title of the Publication	Application	Year
1	3D printing of complex architected metamaterial structures by simple material extrusion for bone tissue engineering (Al Hashimi et al., 2022)	Generation and evaluation of various porous structures (cubic, gyroid, sheet primitive) as a substitute for bone material.	2022
2	3D printing and characterization of a soft and biostable elastomer with high flexibility and strength for biomedical applications (Bachtiar et al., 2020)	Soft and biocompatible elastomer components are examined for their mechanical and biological properties.	2020
3	Printability Study of Bioprinted Tubular Structures Using Liquid Hydrogel Precursors in a Support Bath (Ding and Chang, 2018)	Investigation of the influence of a supporting bath on the manufacturability of soft, tubular implants.	2018
4	Evaluation of Printing Parameters on 3D Extrusion Printing of Pluronic Hydrogels and Machine Learning Guided Parameter Recommendation (Fu et al., 2021a)	Experimental investigation of the influence of process parameters on dimensional accuracy and implementation of an ML algorithm	2021
6	3D printing of gelatin/chitosan biodegradable hybrid hydrogel: Critical issues due to the crosslinking reaction, degradation phenomena and process parameters	Investigation of the effect of ageing processes and other process parameters on workability and dimensional stability.	2021
7	3D printing PLGA: a quantitative examination of the effects of polymer composition and printing parameters on print resolution (Guo et al., 2017)	Comparison of materials with different compositions in terms of degradation, water absorption and compressive strength.	2017
8	Fabrication and characterization of hybrid PCL/PEG 3D scaffolds for potential tissue engineering applications	Investigation of the influence of process parameters on mechanical properties and pore size.	2014
9	Self-Contained Three-Dimensional Bioprinter for Applications in Cardiovascular Research (Kharel et al., 2019)	Development of a bioprinter with a controlled environment and comparison of printed and cast implants.	2019
10	Study on parameter optimization of 3D bioprinting of hybrid bio-inks (James and Mulgaonkar, 2022)	Investigation of the behavior of hybrid bioninks when changing the process parameters. Optimization only possible depending on the material used.	2021
13	3D Direct Printing of Silicone Meniscus Implant Using a Novel Heat-Cured Extrusion-Based Printer (Luis et al., 2020)	Attempt to print difficult-to-process silicone, optimizing in particular with a view to accurate reproduction of the shape.	2020
14	Impact of In-Process Crystallinity of Biodegradable Scaffolds Fabricated by Material Extrusion on the Micro- and Nanosurface Topography, Viability, Proliferation, and Differentiation of Human Mesenchymal Stromal Cells (Luzanin et al., 2023)	Influence of the crystallinity and surface quality of the component on the development of human cells in the implant.	2023

16	Optimization of the additive manufacturing parameters of polylactic acid (PLA) cellular structures for biomedical applications (Myers et al., 2022)	Optimization and prioritization of various process parameters with regard to the influence on mechanical and geometric properties and comparison of different infill structures.	2022
17	Label free process monitoring of 3D bioprinted engineered constructs via dielectric impedance spectroscopy	Development of a system for real-time measurement of cell viability and growth, taking into account various process parameters.	2018
19	Effect of Process Parameters on the Quality of Additively Manufactured PETG-Silk Composite (Vijayasankar and Pati, 2023)	Optimization of process parameters for medical products made of PETG-Silk composite.	2022
20	Printomics: the high-throughput analysis of printing parameters applied to Melt Electrowriting	Development of an automated MEW system for improved control of process parameters and analysis of their influence on product quality.	2019
21	Effects of Six Processing Parameters on the Size of PCL Fibers Prepared by Melt Electrospinning (Xie et al., 2023)	Investigation of the yarn geometry in the context of the MEW process under consideration of various process parameters.	2023
22	Additive-manufactured polycaprolactone scaffold consisting of innovatively designed micro-sized spiral struts for hard tissue regeneration (Yang et al., 2016)	Production of new types of implants with twisted instead of straight thread geometry for improved cell behavior.	2016
23	Characterization of the Functional Properties of Polycaprolactone Bone Scaffolds Fabricated Using Pneumatic Micro-Extrusion	Production of porous bone material in combination with patient-derived stem cells and investigation of the influence of process parameters.	2021
25	Mechanical properties of polycaprolactone (PCL) scaffolds for hybrid 3D-bioprinting with alginate-gelatin hydrogel	Process investigation in the separate processing of polymer and hydrogel for improved mechanical and biological properties.	2022
27	A grey-based Taguchi method to optimize fused deposition modelling process parameters for manufacture of a hip joint implant	Optimization of the process parameters for hip joint implants using FEM analysis and experimental production and evaluation of the components.	2022
28	Fused filament fabrication-3D printing of poly-ether-ether-ketone (PEEK) spinal fusion cages (Saini et al., 2022)	Production and mechanical evaluation of high-strength, printed implants for the spine.	2022
30	Process-Structure-Quality Relationships of Three-Dimensional Printed Poly(Caprolactone)-Hydroxyapatite Scaffolds	Investigation of the influence of process parameters on PCL-Hap composite and in-situ process monitoring	2020

A.4 Literature Review on EAM PP and QA – Key Terms

Number	Method & Materials			
	Extrusion Principle	Machine	Material Category	Base Material
1	Pressure-based extrusion	RegemHU 3D Discovery	Fixed, cell occupied	PCL (polycaprolactone)
2	Motor-based extrusion	Lulzbot Taz 6, Aleph Objects	Soft, cellular	TPU (polycarbonate-based polyurethane silicone)
3	Pressure-based extrusion	In-house development	Soft, cellular	AL-GE (alginate-gelatin)
4	Motor-based extrusion	BioMaker SunP Biotech	Soft	Pluronic F127
6	Pressure-based extrusion	Envisiontec 3D Bioplotter	Soft	GE-PEG (gelatine-polyethyleneglycol)
7	Pressure-based extrusion	Envisiontec 3D Bioplotter	Firm	PLGA (polylactic-co-glycolic acid)
8	Pressure-based extrusion	In-house development	Firm	PCL and PEG (polycaprolactone and polyethylene glycol)
9	Pressure-based extrusion	In-house development	Soft, cellular	AL-GE (alginate-gelatin)
10	Pressure-based extrusion	3D Systems Allevi 3	Soft	AL-GE (alginate-gelatin)
13	Pressure-based extrusion	In-house development	Soft	SI (silicone)
14	Motor-based extrusion	Prusa i3 MK2S FFF	Fixed, cell occupied	PLA (polylactic acid)
16	Motor-based extrusion	Crealiti Ender 3 Pro	Firm	PLA (polylactic acid)
17	Pressure-based extrusion	Envisiontec 3D Bioplotter	Soft, cellular	AL (alginate)
19	Motor-based extrusion	Crealiti Ender 10S Pro	Firm	PETG (short silk fiber reinforced)

20	Electrowriting/spinning	In-house development	Firm	PCL (polycaprolactone)
21	Electrowriting/spinning	In-house development	Firm	PCL (polycaprolactone)
22	Pressure-based extrusion	In-house development	Fixed, cell occupied	PCL (polycaprolactone)
23	Pressure-based extrusion	In-house development	Firm	PCL (polycaprolactone)
25	Motor-based extrusion	Prusa i3 MK3	Fixed, cell occupied	Hybrid, PCL and AL-GE (polycaprolactone and alginate-gelatin)
27	Motor-based extrusion	Fusion 3D 410 printer	Firm	PA12 (carbon fiber reinforced)
28	Motor-based extrusion	Intamsys FUN-MAT HAT Enhanced	Firm	PEEK (poly-ether-ether-ketone)
30	Pressure-based extrusion	Envisiontec 3D Bioplotter	Fixed, cell occupied	PCL (polycaprolactone)

A.5 Overview of Relevant Requirements According to MDR

Table 28: Overview of the relevant requirements of Regulation (EU) 2017/ 745

Quality Management System	Reference
Definition of and compliance with safety and performance requirements	Art. 10 para. 9
Selection and control of suppliers	Art. 10 para. 9
Corrective and preventive measures	Art. 10 para. 9
Measurement/monitoring of results for data analysis and product improvement	Art. 10 para. 9
Product Realization	
Final inspection of the product and monitoring of the production processes	Annex XI para. 4
Quality assurance and control techniques	Annex XI para. 6
Tests and inspections before and during production, their frequency and devices, as well as their calibration, testing and verification	Annex XI para. 6 & 7
Technical Documentation	
Product specifications and safety and performance requirements	Annex II para. 3 & 4
Proof of conformity with the requirements, testing of the end product	Annex II para. 3 & 4
Justification, validation and verification of the methods used for this purpose	Annex II para. 4
Applied manufacturing processes and their validation and monitoring	Annex II para. 3
Risk-benefit analysis, risk management results and solutions	Annex II para. 5
Results and analyses of all relevant verification and validation tests	Annex II para. 6
Applied standards, laws and similar	Annex II para. 4
Risk Management	
Identification and analysis of foreseeable hazards	Annex I para. 3
Assessment and evaluation of risks incl. production	Annex I para. 3
Risk reduction according to the state of the art and in relation to the benefit	Annex I para. 4 & 8
Particular attention must be paid to pollutants, particles and the risk of infection	Annex I para. 10 & 11

A.6 Overview of Relevant Requirements According to FDA

Table 29: Overview of the relevant requirements of FDA Regulation 21 CFR Part 820

Quality Management System	§ 820.
Verification and release/disposal of incoming products/manufacturing materials	70H, 80B
Continuous monitoring of the conformity status of the product during production	80C, 86
Final inspection, comparison with device master record and verification of production data	80 D&E
Control of non-compliant products: Identification, documentation, evaluation, segregation, disposal, revision and testing or special release	90
Determination of causes of non-conformities using all available data, identification, validation, implementation and verification of preventive and corrective measures	100
Statistical procedures for controlling and verifying process capability and product conformity with appropriate sampling plans	250 A&B
Product Realization	
Clear identifiability of the product and its components before, during and after production	60 & 65
Control and monitoring of production processes through documented defining instructions and monitoring and control of process parameters	70A
Regularly inspected environmental control system and contamination control	70 C&E
Appropriate equipment with maintenance schedules, regular inspection and calibration	70G
Regular maintenance and calibration of inspection and test equipment	72A
Calibration against international standards and limit values for accuracy and precision (limit values not achieved: evaluation of the quality of the manufactured products)	72B
Process validation of all processes whose results cannot be fully verified, monitoring and control of the process parameters of validated processes	75
Software validation of automated data processing systems	70I
Avoidance of quality-reducing effects such as mix-ups, damage, decay and contamination of products during handling and storage	140 & 150
Technical Documentation	
Documentation must be legible and stored in a way to prevent deterioration and loss	180
Device Master Record describes product characteristics and defines production processes, -equipment and environment, as well as test processes, equipment and environment	181
Device History Record contains product identification, production date, compliance status and documentation showing compliance with Device Master Record, including process and test data	184
Quality System Record includes non-product specific documentation and procedures	186
Documentation/recording of all listed activities and their results	

A.7 Overview of Relevant Requirements According to DIN

Table 30: Overview of the relevant requirements for QMS integration from the DIN EN ISO 13485

Quality Management System	Chap.
Implementation of the necessary measures to achieve planned goals	4.1.3
Establishment of methods for monitoring, measurement, analysis and improvement	8.1
Monitoring, measuring and analyzing processes to demonstrate and ensure their effectiveness	4.1.3 & 8.2.5
Monitoring and measurement of product characteristics to verify conformity	8.2.6
Control of non-conforming products (identification, documentation, segregation, evaluation, disposition, rework and verification, special release with justification)	8.3
Identification and assessment of causes of non-conformities Implementation and verification of corrective and preventive measures	8.5
Collection and analysis of quality data to demonstrate the effectiveness of the QMS	8.4
Product Realization	
Define requirements for infrastructure, such as buildings and process equipment, regular maintenance of infrastructure	6.3
Monitoring and control of working environment and contamination by CFU or particles	6.4
Ensure that development results and production capabilities match	7.3.8
Criteria for evaluating and selecting suppliers and materials	7.4.1
Verification of the conformity of procured products with the procurement requirements	7.4.3
Procedures to control production, qualify infrastructure, monitor and measure process parameters and product characteristics to ensure that product meets specifications	7.5.1
Validation of the production processes whose result is not verified, including defined acceptance criteria, qualification of equipment, statistical methods with appropriate sampling plan and software validation	7.5.6
Clear identifiability of the product, its conformity status and its components during and after the entire product realization process	7.5.8 & 7.5.9
Protection of the product against alteration, contamination and damage during processing, storage and handling	7.5.11
Calibration or verification of the measuring equipment regularly or before use using international measuring standards, adjustment or readjustment if necessary	7.6
Protect monitoring and measuring equipment from adjustment, damage and deterioration	7.6
Technical Documentation	
Documentation must be legible, easily identifiable and retrievable	4.2.5
Documentation of all listed activities and their results to demonstrate compliance with regulatory requirements and product requirements	4.1.3 & 4.2.5
Risk Management	
Risk-based approach for the management of QM-relevant processes	4.1.2
Risk management in production	7.1

A.8 Selected Devices and Software for Concept Finalization

Table 31 summarizes all the components that were considered for the finalization of the production concept and were partially implemented for the construction of a validation demonstrator, presented in Chapter 3.7.

Table 31: Hardware and software components considered for concept finalization

Hardware Component	Product	Manufacturing Company
Planar Drive System	XPlanar (3x4 Tiles)	Beckhoff Automation GmbH & Co. KG
Static Robotic Arm	VS-087	Denso Robotics Incorporated
Mobile Lab Robot	Kevin	URG GmbH
Granulate Dosing System	CONWEIGH	Volkmann GmbH
Automated Storages	R-TEK/IS2000	R-TEK Intelligent Technology Co., Ltd.
Granulate Extruder	PRINCORE Granulatrextruder	Princore GmbH
Camera	EDGE AF4915ZTL	Dino-Lite
Laser Depth Sensor	S-BOD 6K	Balluff GmbH
Linear Axes	EGSS-BS-KF-32-25	Festo GmbH
Mechanical Structure Parts	Custom	Fraunhofer IPT
Software Component	Product	Developing Company
PLC Environment	TwinCAT 3	Beckhoff Automation GmbH & Co. KG
Process Control Software	COPE	Fraunhofer IPT

A.9 Specification of Cleanroom Classes According to ISO

Table 32: Permissible particle counts and particle sizes for the respective cleanroom classes according to ISO 14644-1 (ISO, 2015)

Class	Maximum Particle Count per m ²					
	≥ 0,1 µm	≥ 0,2 µm	≥ 0,3 µm	≥ 0,5 µm	≥ 1 µm	≥ 5 µm
ISO 1	10	-	-	-	-	-
ISO 2	100	24	10	-	-	-
ISO 3	1000	237	102	35	-	-
ISO 4	10000	2370	1020	352	83	-
ISO 5	100000	23700	10200	3520	832	-
ISO 6	1000000	237000	102000	35200	8320	293
ISO 7	-	-	-	352000	83200	2930
ISO 8	-	-	-	3520000	832000	29300
ISO 9	-	-	-	35200000	8320000	293000

A.10 Overview Tables on Sub Model Function Blocks

Table 33: Brief descriptions of the functions of the individual function blocks of the *Computer* sub model and supplement to the corresponding figure

Number	Name	Function
1	Job.Generator	Generation of print job entities
2	ScaffoldData.Assign	Assignment of the scaffold parameters to the job attributes
3	InputData.FileToMatrix	Reading an input file and importing it into JaamSim
4	ScaffoldData.Distribution	Generation of a normally distributed value based on given marginal values
5	MoverReady.Gate	Gate to release a job when a mover is ready
6	JobForMover.Assign	Reservation of a mover for a job
7	Job.Delay	Technically relevant delay of 1 second
8	MoverOrder.Assign	Setting the mover attributes for the next process steps
9	JobToMover.AddTo	Linking job entity with mover container
10	Mover.Duplicate	Duplication of the mover container
11	PhantomScaffold.Assemble	Assembly of the phantom scaffold entity from the mover duplicate data
12	PhantomScaffoldToMover.AddTo	Linking phantom scaffold entity with mover container
13	PrintData.Assign	Synchronization of the attributes of the entities with those of the mover container

Table 34: Brief descriptions of the functions of the individual function blocks of the *Applicator* sub model and supplement to the corresponding figure

Number	Name	Function
1	Substrate.Generator	Generation of substrate entities
2	MoverReady.Gate	Gate to release a substrate when a mover is ready
3	SubstrateForMover.Assign	Reservation of a mover for a substrate
4	Robot.Seize	Seizure of the robot for the substrate transportation process
5	SubstrateOnMover.Transport	Transportation of substrate from storage to mover
6	Robot.Release	Release of the robot from the substrate transportation process
7	ResetGate.Assign	Reset of the gate signal for further use

8	Mover.AddTo	Linking substrate with mover container
9	MoverWithSubstrate.SetGraphic	Assignment of a new graphic
10	ApplicationTime.Delay	Delay time to simulate the mounting of the substrate on the mover
11	NextExtruder.Assign	Assignment of the coordinates of the extruder to be used for the printing process

Table 35: Brief descriptions of the functions of the individual function blocks of the *Tile* sub model and supplement to the corresponding figure

Number	Name	Function
1	Target.Assign	Assigning target tile to mover
2	Status.Assign	Assigning „Blocked“ status to tile
3	NextTile.Branch	Checking which tile is selected next
4	Reached.Assign	Assigning that the mover reached its destination
5	NextTileDown.Assign	Assigning that the preferred next tile to go is the tile the way down
6	NextTileUp.Assign	Assigning that the preferred next tile to go is the tile the way up
7	NextTileRight.Assign	Assigning that the preferred next tile to go is the tile the way right
8	NextTileLeft.Assign	Assigning that the preferred next tile to go is the tile the way left
9	BlockageCheck.Branch	Checking whether the next tile is blocked
10	CheckPrevious.Branch	Checking whether the mover was on the next planned tile previously
11	BlockageSolver.Branch	Checking whether the blockage should be actively solved or if it should be waited
12	Waiting.Assign	Assigning „Waiting“ status to tile and mover
13	FullBlockageDetect.Branch	Checking whether a mover is completely blocked
14	Redirecting.Delay	Delay before redirecting to an alternative path
15	HomeReset.Assign	Resetting the <i>WaitCounter</i> to 0
16	PreventPrevious.Branch	Checking whether moving to the previous tile should be prevented
17	PreventPrevious.Distribution	Probability of preventing a return
18	Leaving.Assign	Assigning the mover as leaving and resetting the tile status
19	Redirecting.Branch	Checking which alternative path a mover can take
20	Random.Distribution	Randomization to decide between equally valid paths

21	Priorisation.Branch	Checking which mover has priority in case of two movers blocking each other
22	WaitReset.Branch	Checking if a mover should continue to wait to get to its desired direction
23	WaitCounter.Assign	Counter to prevent unlimited waiting
24	Tile.Server	Defines the cycle time with which a mover requests what it should do next
25	Exit.Branch	Checking whether the mover has reached a station to carry out a process or reached its home position
26	Update.Delay	Defines the time after which a new check is made as to whether a mover has been given a new destination
27	Update.Branch	Checking whether a mover has been given a new destination
28	Home.Assign	Assigning the “Home” status to tile and mover
29	Directing.Branch	Directing the mover to the correct sub model exit to the next tile

Table 36: Brief descriptions of the functions of the individual function blocks of the *Extruder*-sub model and supplement to the corresponding figure

Number	Name	Function
1	Extruder.Server	Simulating the extrusion process in terms of processing time
2	LayerCountUp.Assign	Incrementes the <i>LayerCount</i> by 1
3	Defect.Branch	Decides whether or not the printed layer has an error
4	Defect.Distribution	Probability of a faulty print layer
5	PrintProgress.SetGraphic	Assigns a new graphic to the mover
6	Defect.Assign	Assigns the <i>QualityStatus</i> of the mover to “UndetectedDefect”
7	Defect.SetGraphic	Assigns a new graphic to the mover
8	NextStation.Branch	Checks whether a QC is to be carried out next
9	NextHome.Assign	Sets the <i>MoverTargetTile</i> to the coordinates of the mover home position
10	NextImager.Assign	Sets the <i>MoverTargetTile</i> to the coordinates of the Imager position
11	Mover.Duplicate	Duplicates the mover to start a parallel process
12	CoolDown.Delay	Delays the mover
13	NextExtruder.Assign	Sets the <i>MoverTargetTile</i> to the coordinates of the Extruder position
14	Mover.Delete	Deletes the mover duplicate

Table 37: Brief descriptions of the functions of the individual function blocks of the *Scanner* sub model and supplement to the corresponding figure

Number	Name	Function
1	Scanner.Server	Simulating the scanning process in terms of processing time
2	QualityCheck.Branch	Simulates the test to check whether the quality of the scaffold is sufficient
3	Quality.Distribution	Probability of a scaffold passing the QC test
4	Passed.Assign	Assignment of the <i>QualityStatus</i> attribute to “Passed”
5	Failed.Assign	Assignment of the <i>QualityStatus</i> attribute to “Failed”
6	NextSeparator.Assign	Sets the <i>MoverTargetTile</i> to the coordinates of the separator position

Table 38: Brief descriptions of the functions of the individual function blocks of the *Imager* sub model and supplement to the corresponding figure

Number	Name	Function
1	Imager.Server	Simulating the imaging process in terms of processing time
2	SortDefect.Branch	Sorting of “DefectFree” and “UndetectedDefect” scaffolds
3	DefectFree.Branch	Simulation of an imaging test whether a false defect is detected
4	FalseNegative.Distribution	Probability of a false negative test result
5	Defect.Branch	Simulation of an imaging test whether a true defect is detected
6	TrueNegative.Distribution	Probability of a true negative test result
7	DefectDetected.Assign	Change of <i>QualityStatus</i> to “DefectDetected”
8	NextSeparator.Assign	Sets the <i>MoverTargetTile</i> to the coordinates of the separator position
9	CompletionCheck.Branch	<i>RequiredLayers</i> and <i>PrintedLayers</i> attributes are checked for a match
10	FalseDefectDetected.Assign	Change of <i>QualityStatus</i> to “FalseDefectDetected”
11	NextExtruder.Assign	Sets the <i>MoverTargetTile</i> to the coordinates of the extruder position
12	NextScanner.Assign	Sets the <i>MoverTargetTile</i> to the coordinates of the scanner position

Table 39: Brief descriptions of the functions of the individual function blocks of the *Separator* sub model and supplement to the corresponding figure

Number	Name	Function
1	Job.Remove	Print Job entity is taken from the Mover container
2	JobCompletion.Branch	Checking whether the job was successfully completed
3	FinishedJob.Logger	Logging the the data of a finished job
4	FinishedJob.Delete	Deleting the job
5	JobRestart.Assign	Initiating the print job restart
6	Robot.Seize	Seizure of the robot resource for the separation procedure
7	Scaffold.Remove	Substrate with Scaffold is removed from mover container
8	MoverReset.Assign	Mover attributes are reset to default values
9	Mover.SetGraphic	Default mover graphic is assigned
10	WithoutMover.SetGraphic	Finished or broken scaffold graphic is assigned
11	DefectSort.Branch	Finished and broken scaffolds are separated
12	ToRecycler.Transport	Simulation of the separation and transportation procedure to the waste bin
13	Robot.Release	Release of the robot resource from the separation and transport procedure
14	DefectScaffold.Logger	Logging all process times the individual scaffold went through until the defect
15	ToStorage.Transport	Simulation of the separation and transportation procedure to the scaffold storage
16	Robot.Release	Release of the robot resource from the transport procedure
17	FinishedScaffold.Logger	Logging all process times the individual scaffold went through until completion

A.11 Model Configuration for a Larger Scale Production

The manual configuration of the production model shown in Figure 66, is carried out in the same way as described for Table 16. The specific attributes of the scaled model are listed in Table 40.

Table 40: Attributes of the planar drive model that have to be configured manually for the demonstrator scenario

Line	Planar Drive Tile Attributes	Definition
1	TileArray	'{ { 1,1 }, { 2,1 }, { 3,1 }, { 4,1 }, { 5,1 }, { 1,2 }, { 2,2 }, { 3,2 }, { 4,2 }, { 5,2 }, { 1,3 }, { 2,3 }, { 3,3 }, { 4,3 }, { 5,3 }, { 1,4 }, { 2,4 }, { 3,4 }, { 4,4 }, { 5,4 }, { 1,5 }, { 2,5 }, { 3,5 }, { 4,5 }, { 5,5 }, { 1,6 }, { 2,6 }, { 3,6 }, { 4,6 }, { 5,6 }, { 1,7 }, { 2,7 }, { 3,7 }, { 4,7 }, { 5,7 }, { 1,8 }, { 2,8 }, { 3,8 }, { 4,8 }, { 5,8 }, { 1,9 }, { 2,9 }, { 3,9 }, { 4,9 }, { 5,9 }, { 1,10 }, { 2,10 }, { 3,10 }, { 4,10 }, { 5,10 }, { 1,11 }, { 2,11 }, { 3,11 }, { 4,11 }, { 5,11 }, { 1,12 }, { 2,12 }, { 3,12 }, { 4,12 }, { 5,12 }, { 1,13 }, { 2,13 }, { 3,13 }, { 4,13 }, { 5,13 }, { 1,14 }, { 2,14 }, { 3,14 }, { 4,14 }, { 5,14 } }'
2	MoverHomeTiles	'{ { 2,1 }, { 4,16 }, { 5,8 }, { 1,4 }, { 5,13 }, { 1,7 }, { 1,6 }, { 1,11 }, { 1,9 }, { 5,4 }, { 1,13 }, { 5,12 }, { 5,2 }, { 1,15 }, { 1,2 }, { 5,15 }, { 4,9 }, { 2,3 }, { 4,14 }, { 2,8 }, { 2,5 }, { 2,12 }, { 2,10 }, { 4,3 }, { 2,14 }, { 4,11 }, { 4,1 }, { 2,16 } }'
3	ExtruderTiles	'{ { 1,1 }, { 5,16 }, { 5,9 }, { 1,3 }, { 5,14 }, { 1,8 }, { 1,5 }, { 1,12 }, { 1,10 }, { 5,3 }, { 1,14 }, { 5,11 }, { 5,1 }, { 1,16 } }'
4	ImagerTiles	'{ { 3,1 }, { 3,16 }, { 5,10 } }'
5	ScannerTiles	'{ { 5,7 } }'
6	ApplicatorTile	'{ 5,5 }'
7	SeparatorTile	'{ 5,6 }'

A.12 Simulation Data Access

All data and models for reproducing the simulation results using JaamSim can be accessed via this link:

<https://owncloud.fraunhofer.de/index.php/s/1X20hE61HIAm1fP>

with the password:

SPIfEbAMoPMS2025