

## Article

# Implementation of a Digital Twin in Additive Manufacturing of Copper—Methodology, Implications, and Future Prospects

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## Abstract

Digital twins are increasingly being used to visualize, analyze, or control physical processes and systems. Implementation currently poses challenges for users due to the cross-domain complexity of digital twins. In this study, the authors utilize a self-developed method to support the implementation of a digital twin (DT) for a powder bed fusion additive manufacturing system (PBF-LB/M) for copper components, utilizing a green laser. The study highlights the support offered by the developed approach and the implications of using DTs for PBF of copper. The DT focuses in particular on monitoring maintenance requirements, assisting in the selection of correct process parameters, and alerting plant operators in the event of problems. In addition, a process model focused on lack of fusion is implemented, based on earlier studies. In the human–machine system, DTs thus represent a further building block towards an improved process stability in PBF-LB/M of copper, and the method used lowers the barrier to entry for widespread use of DTs.

**Keywords:** digital twin; additive manufacturing; digitalization; copper; PBF; green laser

## 1. Introduction

A digital twin is based on the synchronization between a physical process and its digital representation. Potential applications for DTs extend across the entire life cycle of the associated physical product. In particular, the concept of DTs opens new opportunities for the development of product-service systems. The utilization of machine data through status and prediction models, as well as the processing of real-world usage scenarios in product development, are central to this [1]. For these reasons, there is growing interest in the technology among industrial users [2]. However, the implementation of digital twins is challenging, among other things due to its high degree of interdisciplinarity, and poses a major challenge for many companies [3]. In particular, potential users lack a holistic development approach that combines the disciplines of modeling, sensor design, and IT infrastructure in a common model [4]. This problem has been recognized and is therefore being addressed more and more frequently in current studies. The complexity of implementing DTs for users who are inexperienced with the technology is particularly challenging when the physical product for which the DT is to be implemented is highly complex. This is especially true for the powder bed based additive manufacturing process using lasers (PBF-LB/M) and the corresponding manufacturing systems. While additive manufacturing (AM) in general and PBF-LB/M in particular have achieved a sufficient technological maturity, challenges like part quality and productivity remain. Processing of



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pure copper via PBF-LB/M is remarkably complex because of the extraordinary properties of copper regarding laser reflectivity and thermal conductivity.

This study therefore deals with the implementation of a DT for a PBF-LB/M system for processing copper. The methodology developed by Fett for implementing DTs is applied and shortcomings are critically discussed. The result of the approach in the form of a DT is presented and a reference to previous studies is made, especially regarding the combination with process models for the mitigation of lack of fusion in copper PBF. The outlook presents approaches for continuing research into the implementation of DTs and the PBF-LB/M process for copper.

### *1.1. Implementation of Digital Twins*

Since its introduction in 2010 [5], the term “digital twin” has undergone constant change, shaped by both technological progress and a multitude of academic and industrial publications and definitions [6,7]. This has resulted in different and sometimes contradictory interpretations of the term. In this article, the definitions of the Scientific Society for Product Development (WiGeP) [1], the International Organization for Standardization (ISO) [8,9], the Digital Twin Consortium [10], and the Industrial Digital Twin Association (IDTA) are used, which are consistent with each other.

According to these definitions, a digital twin is a digital representation of a physical system, which in this context is also referred to as a physical twin. Selected characteristics, states, or behaviors of the physical twin are described in models within the digital twin. Digital twins differ from conventional simulation models primarily in that they are fed by real operating data, which is collected by sensors or taken from the operating control system. This also requires a suitable IT infrastructure.

The development of digital twins is a complex and interdisciplinary task [11]. Suitable process models and methods can help to make the development process more effective and efficient. In preliminary work, Fett et al. reviewed and analyzed the state of the art of such process models [12]. Building on this, they proposed sub-processes for the development of the models [12], sensors [13] and IT infrastructure [14] underlying the digital twin, which they then summarized in a holistic process model based on the V-model [4]. This approach was also used to develop the digital twin in this work and is described again in Section 2.2.

### *1.2. Digital Twins in PBF-LB/M Systems*

In the context of the PBF-LB/M process, DTs are used for process monitoring, adjustment of process parameters, numerical forecasting, cost prediction, and, in particular, for recording and analyzing the KPIs of the component and the manufacturing process [15]. Another trend in process monitoring with DTs is dynamic control of the system to prevent errors [16]. Error prevention right from the outset is a vital part of total quality management (TQM). This philosophy aims at the improvement of process stability, rather than implementing quality control processes on finished parts. This results in the reduction of scrap and rework and leads to a more efficient utilization of machines [17]. The basic prerequisite for successful TQM is the continuous improvement of existing processes. For this reason, process parameters and the resulting expected outcomes must be determined and applied, which necessitates the documentation of relevant characteristics and the storage of process-relevant information [18]. The use of a digital twin to perform these tasks makes sense due to the extensive process monitoring and analysis options already mentioned and the easier access to data from sensors or the machine software. Krückemeier is developing a digital twin for this purpose for virtual component testing, taking into account the entire product development process and focusing on virtual test plans [19]. Wittmeir et al. use a similar concept to examine the pre- and post-processes of additive manufacturing in particular [20].

Process monitoring for the PBF-LB/M process is an area where DTs are often applied, e.g., in in-situ defect detection [21]. Optical methods include monitoring the melt pool and the spray pattern there using high-speed cameras or observing the component surface and powder distribution using high-resolution cameras. In both cases, classification algorithms based on machine learning are often used. Alternatively, components can be examined for distortion, surface roughness, and geometric errors using 3D scans, either with a setup consisting of two cameras or a setup consisting of a laser and a camera. Another option are acoustic methods, in which the component is examined either by means of ultrasound or by analyzing the emitted sound. The operating principle of ultrasonic testing is based on the echo of the emitted sound waves, which can be used to detect defects in the component. The aim of observing the emitted sound is to detect cracks caused by thermal stresses that emit noise at an early stage [21]. Nath et al. use a probabilistic approach to estimate component porosity, based on an estimate of the geometry of the melt pool [22]. Thermal process monitoring also provides special insights into the process. Here, a heat conduction model is used to determine the temperature distribution and the temperature curve over time in the component, which enables fault and property predictions [21]. However, knowledge of the microstructure is essential in order to be able to assess the properties and faults at the component level [23].

The unit costs of a product can be calculated in the context of the PBF-LB/M process with digital twin using time-driven activity-based costing (TDABC), whereby the cost estimate depends on the processing time required. A distinction is made between time spent on customer service like processing orders, inquiries, and credit checks and time spent on manufacturing capacity regarding resources, personnel, and equipment. Using the digital twin, corresponding key figures can be derived, which improves cost forecasts and reveals new optimization potential [24].

Another component-specific aspect of data collection is the sustainability assessment with regard to environmental and climate impacts. Recorded consumption of gases, materials, and electrical energy is often used for DTs via system-specific or additionally installed sensors. This information is relevant for conducting life cycle assessments (LCA). Automatic data analysis to support LCA from product creation onwards represents another application of DTs.

### *1.3. PBF-LB/M of Copper*

PBF-LB/M is becoming increasingly popular as a manufacturing process for metals [25]. This is particularly true for the processing of iron, titanium, and aluminum-based metallic materials. The PBF-LB/M process enables the production of particularly complex structures, by layer-wise melting of powder under an inert gas atmosphere. Copper is also processed using the PBF-LB/M process, but proves to be more challenging [26]. Recent publications point to a wide variety of problems. Copper has a high reflectivity for infrared laser radiation. Optical components in PBF systems can therefore be damaged by reflected laser beams. The low absorption of the energy introduced also reduces process efficiency. The outstanding thermal conductivity of copper leads to very rapid cooling of the molten pool, which promotes the occurrence of process-typical defects such as warping and layer detachment. Another critical issue is the reduction in the relative density of manufactured components and samples due to incomplete melting of powder and the resulting lack of fusion defects [26]. Despite these challenges, the number of viable applications for additively manufactured components made of copper or copper alloys is increasing, even in demanding industries. In addition to PBF, AM technologies such as wire arc additive manufacturing (WAAM) are also being used [27].

Additive manufacturing processes have a significant influence on the properties of the manufactured components, which is why studies compare the properties of additively manufactured copper parts with conventionally manufactured parts. Malec et al. investigate direct metal laser sintering, a process that is essentially identical to the PBF-LB/M process. The electrical conductivity is slightly lower, at 98.5% of the IACS value. In contrast, the hardness measured after production corresponds to the H80 condition for copper, which is higher than the value achieved in sand casting, for example [28].

The PBF based AM is not limited to specimens for material testing and process development. Qu et al. demonstrate the precise manufacturing of triply periodic minimal surfaces (TPMS) structures [29]. Electrodes for electrical discharge machining (EDM) can also be manufactured using PBF-LB/M for copper [30]. Utilizing the high thermal conductivity of copper and the design freedom of AM, heat sinks offer a another promising field of application for copper PBF [31].

Research into additive manufacturing using PBF-LB/M of copper ranges from sufficient technological maturity for implementation in applications to the still topical issue of process errors and processing difficulties, which are being addressed in current research. While defect free parts are still not achieved reliably, complex composite materials and alloys, the process property relationships in PBF-LB/M of copper, and the utilization of AM in demanding applications are researched. Surpassing material properties achieved by conventional manufacturing processes and tailoring of material properties are potentials which drive the development of AM for copper.

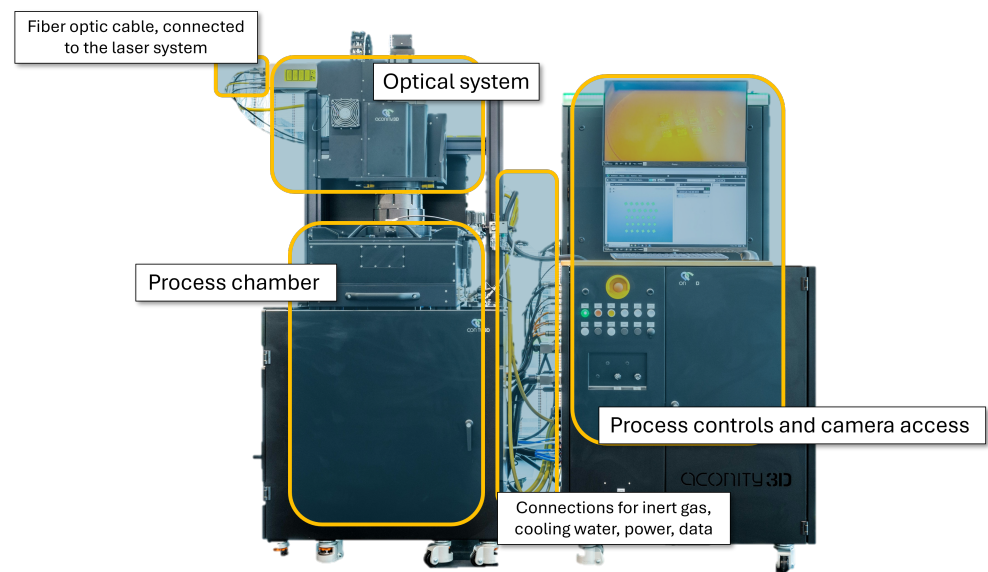
## 2. Materials and Methods

In accordance with the stated objective of this study, a DT for a PBF system for processing metallic powders is implemented. The DT in its current stage of development serves as a basis for further development, within the framework of which additional sensors and functions can be integrated.

### 2.1. PBF-LB/M System

The utilized system is manufactured by Aconity3D GmbH, Germany. This AconityMIDI is equipped with a laser system with a maximum power of 200 W. The laser wavelength is approximately 532 nm, which corresponds to visible green light. Shielding laser radiation in the green wavelength range is more complex to implement than shielding infrared wavelengths. Therefore, this system only allows viewing inside the process chamber using a camera, which consequently plays a very important role in monitoring the process. It is possible to automatically take and store camera images.

Figure 1 provides an illustrative overview of the AconityMIDI PBF system, which was subject to the implementation of a DT in this study. Separate parts of the system that are not shown include the laser cooling system, the gas recirculation system, and the associated cyclone filter. The process chamber contains two cylinders, one of which one of which functions as powder supply and the other as build volume. They are both 170 mm in diameter and have a maximum travel range of 250 mm. During the process, the process chamber is flushed with argon, and the oxygen concentration is usually less than 20 ppm. The substrate plates used are made of corrosion-resistant steel, for example grade 316 L. The optics allow dynamic beam adjustment with regard to the focus diameter of the laser. Typically, the value for the focus diameter on the substrate plate ranges between 50 and 80  $\mu\text{m}$ . The recoater can be equipped with various attachments, such as steel blades or silicone lips. However, carbon fiber brushes are typically used in the process, which help to ensure that the process has a certain degree of resilience with regard to distortion of the manufactured part.



**Figure 1.** Overview of the utilized PBF system AconityMIDI with designation of the most important system sections.

The system has various wear parts located in the process chamber, the optical path, and the protective gas system. The slides of the powder reservoir and the substrate plate are equipped with seals to prevent the powder from escaping. These wear out due to friction with the chamber walls and must be replaced regularly. The carbon fiber brush of the coater also wears out due to friction with the powder and in the event of distortion of the manufactured part. The process chamber is sealed at the top by a boron nitride glass disc. This allows the laser beam to expose the substrate plate. Since deposits on the glass would weaken the laser beam and possibly lead to burn marks, the glass is cleaned before the process begins. This cleaning, among other things, can cause scratches on the glass, which can weaken or deflect the laser. The glass must therefore be checked and replaced if necessary. The gas atmosphere in the process chamber is controlled during the process by initial purging and subsequent sealing. The protective gas supplied during the process absorbs particles produced by the laser-powder interaction. This gas is passed through several filter systems to capture these particles. The filters absorb particles and must therefore also be replaced.

A special feature of this type of PBF system is its modular design. The process chamber can be removed from the surrounding system segment containing the laser optics, laser, and supply connections. This allows for quick changes between process chamber configurations. However, this special feature also underscores the importance of a highly flexible DT design so that new sensors or system functions can be implemented quickly.

## 2.2. Utilized Methodology for DT Implementation

The modified V-model according to Fett et al. is used to implement the digital twin [4]. The complete process can be seen in Figure 2. The figure shows the various phases of implementation, the necessary sub-steps, and outlines the integration of other disciplines into the methodology.

First, the system is broken down into the areas of models, sensors, and IT infrastructure. Requirements are formulated for these sub-areas, which are then combined to form the requirements for the overall system. Based on this, the system architecture is defined, whereby the requirements are transferred to the components and specified in more detail. The subsystems are then implemented and subsequently integrated into an overall system. Finally, the system is validated. At the same time, the branches “requirements management”

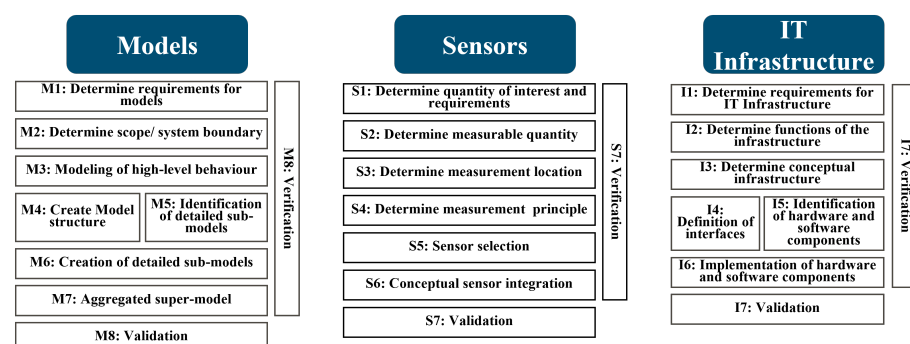
and “modeling and analysis” are combined under the heading “cross-disciplinary” [4]. The development of the digital twin is classified as a sub-process in the work steps “design of the system architecture” and “implementation of the subsystems”.

First, the requirements to be addressed by the digital twins are defined (M1). In this study, the requirements for the DT are derived from its use with regard to process preparation, system preparation, and process monitoring. In the second step, the behaviors and mechanisms necessary to meet the requirements are identified (M2). By subsequently breaking these down into sub-behaviors, the complexity of the higher-level behaviors becomes manageable (M3). In the fourth step, a model structure is created from the sub-behaviors (M4), whereby observable behaviors are converted into observable mechanisms. The identified mechanisms are then transferred to calculation models and implemented (M5). The implemented submodels are then combined into a higher-level model (M6). Parallel to the modeling phase, but especially following the previous seven steps, the work results are verified and validated (M7).

Based on the requirements for the sensor technology, which include the measurement task itself, the location of use, and the interface (S1), the measured variable is determined (S2). This is necessary because the variables of interest are often not directly measurable and, if necessary, alternative measured variables from which the variables of interest can be derived as directly as possible must be identified. Closely related to the measured variable is the determination of the measurement location (S3), which also influences data quality. After determining the measurement principle (S4), sensor selection (S5) begins, drawing on the findings from previous steps. The sensor technology is then integrated into the system (S6) and finally verified (S7).

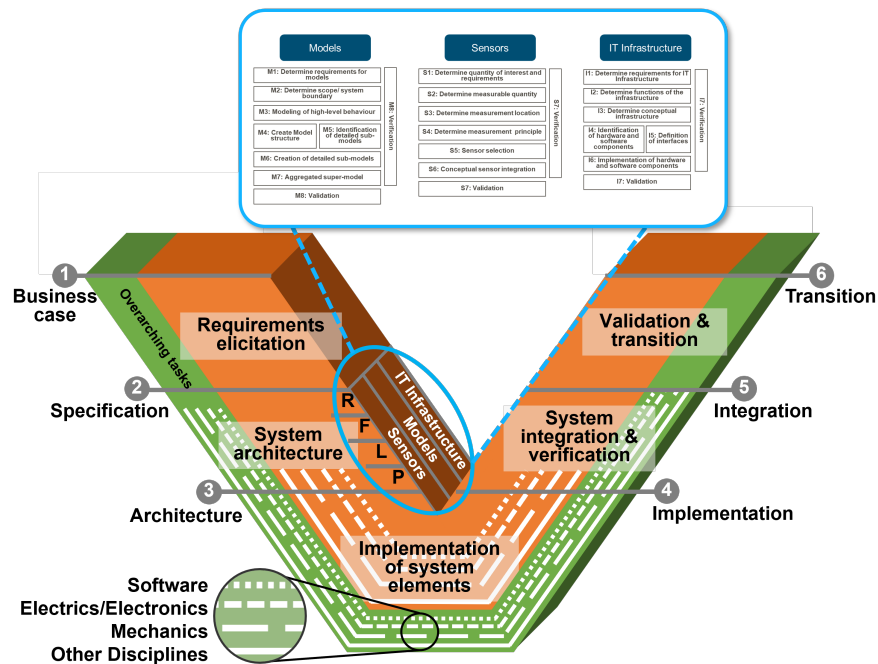
As in the two previous steps, the requirements for the IT infrastructure must first be determined and defined. The most relevant factors here are the expected data volumes, access options for the software, and any real-time capabilities (I1). Once the requirements have been defined, specific sub-functions can be derived from them (I2). Before these functions can be implemented, a plan for the system architecture must first be drawn up (I3), which in turn is decisive for the selection of the necessary hardware and software components (I4). Next, the interfaces apparent from the system architecture are defined and elaborated, whereby communication protocols, for example, must be considered (I5). Based on the previous considerations, implementation can now begin (I6), which is then validated (I7). This procedure should also be approached iteratively, whereby the interim results should always be verified in parallel with the processing.

Figure 2 provides an overview of all the necessary steps involved in the methodology.



**Figure 2.** Necessary steps for implementing a DT in accordance with Fett’s methodology, divided into models, sensors, and IT infrastructure.

The method is based on the V-model from the VDI standard VDI/VDE 2206 “Development of mechatronic and cyber-physical systems.” Accordingly, Figure 3 shows how the work steps shown in Figure 2 fit into the V-model.



**Figure 3.** The adapted V-model for implementing a DT, emphasizing the classification of the work steps to be performed, which are assigned to the RLFP approach.

### 3. Results

The results of this study consist of the comprehensible and fully documented methodology that was applied to the introduced use case of a DT for a PBF system. The implemented and operational DT can also be attributed to the results of the study.

#### 3.1. Methodology Based Implementation

Before implementing DTs, an analysis of the application context and the requirements of the stakeholders involved is carried out, followed by conceptualization. Required functions and general requirements can only be determined by identifying areas where action is needed, which must be defined based on user expectations and existing problems. This applies to all technical products.

The implementation of the digital twin serves to support plant operators with varying levels of experience and expertise. Researchers with a high degree of experience with a wide variety of metal additive manufacturing plants work at AconityMIDI alongside students, assistant scientists, and researchers at the beginning of their careers in the AM field. This heterogeneity of users is also found in the industrial environment, where employees with different levels of training are also required to perform similar or identical tasks on PBF systems. A secondary function of the DT implementation is to test the development methodology developed by Fett.

Requirements can generally be divided into the categories of functionality, usability, reliability, performance, and maintainability [32]. The focus of requirements analysis is less on requirements that are dictated by existing constraints. These are taken into account during implementation, but the system is not modified, as this is outside the scope of this study. For this reason, the focus of identified requirements is on the categories of functionality and usability.

The PBF system under consideration often manufactures components over a period of several days. Process monitoring directly at the plant is therefore not practical, nor is continuous monitoring by an operator possible. Errors that occur can therefore not be addressed directly. After a process interruption, while there is data available in the form of

process log-files or images, it is difficult to link anomalies to the exact occurrence of defects. This makes preventing defects or process interruptions more challenging compared to live process monitoring during defect formation, which allows for a more direct investigation of the problem. There is a high degree of component individuality. If key figures on productivity, sustainability, or the manufacturing behavior of the system are to be collected, this must be done for each production run. A real-time display of the data should allow an assessment of the machine status.

The DT to be implemented must be designed in such a way that its range of functions can be adapted to future requirements. With regard to use in a real production environment, as opposed to use in a research facility, data on productivity and sustainability will become increasingly important. In order for corresponding models to be integrated into the DT, it is necessary to collect data on all consumption in the process, in particular on the consumption of electrical energy.

In the system context, there are several actors that interact with the DT or are part of it. These are the software, models and associated parameters, measurement data, and the presentation of these as components of the DT. Actors that interact with the DT are the PBF system, external sensors, and the machine operators or supervisors of the process. Based on the usage context described above, requirements are formulated and summarized in Table 1.

**Table 1.** Requirements for data output, interfaces and compatibility of the DT with requirements designated as fixed requirements (FR), target requirements (TR), and wishes (W).

| Structure     | Type | Designation                                   | Requirements Values, Data, Description                                                                                                                                                              |
|---------------|------|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Output data   | FR   | Record process parameters                     | Record user-controlled process data and make it available for export for further processing.<br>Minimum required data: Wear, energy input                                                           |
|               | TR   | Limit output to relevant data                 | Provide data sets that are as compact as possible by identifying and isolating relevant characteristics.<br>Limit data sets by using customizable permissible ranges ( $x_{\min} < x < x_{\max}$ )  |
|               | W    | Present in a visually appealing way           | Use colors and analogous symbols to improve communication                                                                                                                                           |
| Interfaces    | FR   | Allow user interactions                       | Provision of a graphical user interface with buttons and text fields                                                                                                                                |
|               | FR   | Allow data export                             | Provide data for further processing                                                                                                                                                                 |
|               | FR   | Reading an external (electrical power) sensor | Provide interface for external sensor for monitoring electrical power consumption                                                                                                                   |
|               | W    | Data access from outside the lab location     | Notification of responsible persons upon detection of an error                                                                                                                                      |
| Compatibility | W    | Transferability to other PBF systems          | Machine-specific information in configuration files can be modified by users: material used, sensor configuration and sensor access data, machine access data, customizable maintenance information |
|               | W    | Switching between process and machine models  | Decision rules used to identify characteristics should be customizable by users                                                                                                                     |
|               | FR   | Compatibility with the system PC              | Compatibility with Windows 11, 1920 × 1080 screen, mid-range CPU, use of local storage                                                                                                              |
|               | FR   | Allow for remote maintenance access           | Maintaining the currently usable internet connection                                                                                                                                                |

### 3.1.1. Models

The models are one of the basic elements of the digital twin and are directly dependent on the task at hand. The aim of this first step is therefore to select existing calculation models

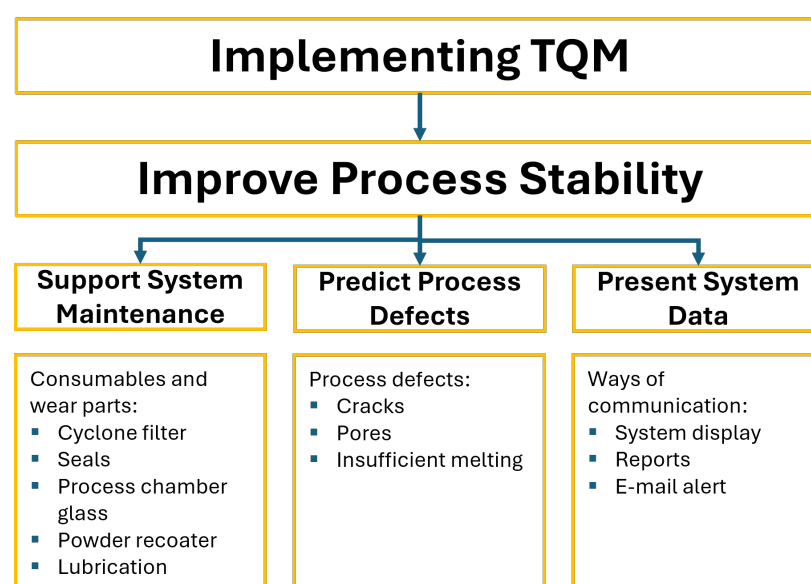
and develop a model structure to implement models able to facilitate quality management and improve process stability. In particular, with regard to the requirements from Table 1, it is possible to define, which models are necessary:

- A predictive model for pre-designing the process with regard to the expected relative density depending on the process parameters
- A decision model that checks the possibility of starting the process based on the current system status
- A descriptive model for describing the current production run for monitoring and error detection

The following requirements can be formulated across all models:

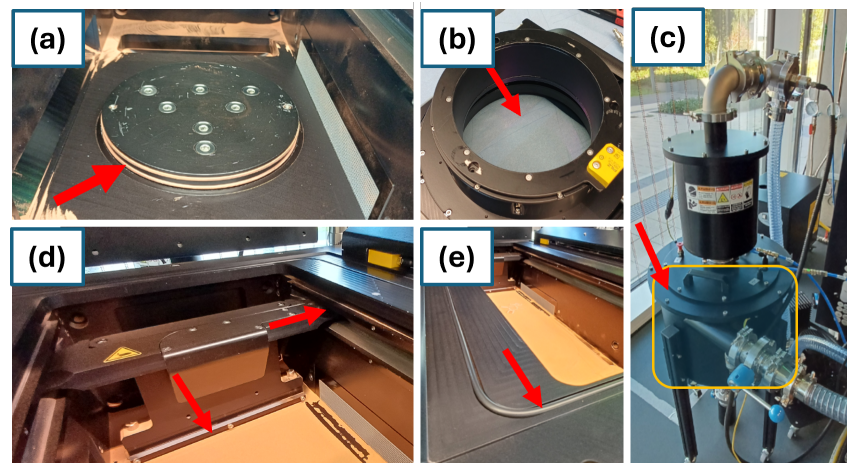
- Only metrics for which the necessary sensors are already available are used.
- A high degree of abstraction in the models is acceptable due to the many factors influencing the PBF-LB/M process
- Models can also be used with approximate values
- Analytical and descriptive models are combined
- The condition and damage to parts of the PBF system are considered separately
- Models verified by accompanying research are used
- Data is sampled at a frequency of 1 Hz or less
- The total computing time required to update all models is less than 30 ms

Based on the determination of the requirements for the models and the aim of contributing to TQM in the PBF-LB/M process, the implementation of these models is divided into the following sub-items of support system maintenance, predict process defects and present system data, as shown in Figure 4. The behavior “Detect process errors” describes the identification of possible component errors, which includes both observing the process conditions and mathematically estimating the occurrence of common errors in additive manufacturing. In addition, this behavior revisits the plausibility check of the process parameters from the DT concept. The behavior “maintain infrastructure” encompasses the usage-based derivation of maintenance requirements. The presentation of the model results enables intervention in the process and systematic processing of the results via human–machine communication interfaces.



**Figure 4.** Model structure with the desired model behaviors of supporting system maintenance, predicting process defects, and presenting system data and the corresponding substructure.

Figure 5 shows a selection of especially relevant wear parts considered in the DT. Wear mechanisms can be described by analytical models. The influence of wear and tear on machine parts in the PBF process is part of existing research and the process relevance of an insufficient inert gas supply, of damaged optical components, damaged seals, and insufficient lubrication are known [33–36]. In this case, the modeling of wear and tear in the PBF system is done purely based on operating time and movement of seals. This approach is not analytical and therefore difficult to transfer to other PBF systems. However, implementation in a DT is very simple and the accuracy for the specific application is very high, as the specified limit values are based on experience.



**Figure 5.** Wear parts whose remaining service life is tracked by the DT, arrows indicating exact positions: (a) build platform seals (b) process chamber glass (c) cyclone filter enclosing by a metal housing (d) powder recoater and lubrication point for linear bearings (e) process chamber seal.

Table 2 summarizes the limitations for the service life without testing or replacing wear parts from Figure 5.

**Table 2.** Tabular overview of wear parts monitored by the DT, specifying the criteria for checking or replacing the component, the assignment to a component type, and the specified usage limits.

| Component Type           | Part                       | Model Criteria                                                                                                          |                                                                      |
|--------------------------|----------------------------|-------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|
|                          |                            | Criterion for Wear Assessment                                                                                           | Values for Operating Limits                                          |
| Seal                     | Build platform seals       | Summed up movement of the build platform $\sum z_{move}$ in millimeters (mm)<br>OR number of built jobs $\sum i_{jobs}$ | $\sum z_{move,max} = 1.250 \text{ mm}$<br>OR $\sum i_{jobs,max} = 5$ |
|                          | Process chamber seal       | Service time $t_{chamber \text{ seal}}$ in hours (h)                                                                    | $t_{chamber \text{ seal},max} = 8.760 \text{ h}$                     |
| Wear parts               | Powder recoater brush      | Service time $t_{brush}$ in hours (h)                                                                                   | $t_{brush,max} = 300 \text{ h}$                                      |
|                          | Lubrication linear bearing | Service time $t_{lubrication}$ in hours (h)                                                                             | $t_{lubrication,max} = 720 \text{ h}$                                |
| Miscellaneous components | Process chamber glass      | Service time $t_{chamber \text{ glass}}$ in hours (h)                                                                   | $t_{chamber \text{ glass}} = 1.000 \text{ h}$                        |
|                          | Cyclone filter             | Differential pressure $\Delta p_{cyclone}$ in millibar (mbar)                                                           | $\Delta p_{cyclone,max} = 50 \text{ mbar}$                           |

The user interface of the PBF system provides all the information necessary for a trained operator or a supervisor positioned independently of the plant to monitor the criteria for starting the process. However, it is the operator's responsibility to set the correct values and monitor compliance with limit values before starting the process, which are listed in Table 3. This increases the training requirements for the operator and makes errors or deviations from approved process parameters more likely. The DT supports

process reliability here by using model-based monitoring of readiness for process start and translating complex parameters into a simple form according to a OK/Not OK scheme.

**Table 3.** Tabular overview of the monitored process parameters for assessing the possibility of starting the process, with an assignment to the topic area of laser or process atmosphere, the criterion under consideration, and the limits for a successful process start.

| Parameter Category | Process Parameter | Model Criteria                                                                                        |                                                      |
|--------------------|-------------------|-------------------------------------------------------------------------------------------------------|------------------------------------------------------|
|                    |                   | Criterion for Process Readiness                                                                       | Limits for Process Readiness                         |
| Atmosphere         | Oxygen level      | Oxygen fraction $O_{2,ppm}$ in parts per million (ppm)                                                | $O_{2,ppm} \leq 100$                                 |
|                    | Excess pressure   | Excess pressure in the process chamber $\Delta p_{chamber}$ in millibar (mbar)                        | $\Delta p_{chamber} \geq 50$                         |
|                    | Fume extraction   | Status of fume extraction on/off<br>AND fume extraction power setting $p^{s_{fume\ extraction}}$ in % | Status = on<br>AND $p^{s_{fume\ extraction}} > 10\%$ |
|                    | Inert gas flow    | Argon gas flow $\dot{V}_{Ar}$ in liters per minute (L/min)                                            | $\dot{V}_{Ar} \geq 2$                                |
| Laser              | Laser cooling     | Status of cooling system on/off                                                                       | Status = on                                          |
|                    | Laser error       | Number of errors present                                                                              | Errors = 0                                           |

The most relevant possible process defect occurring in the considered copper PBF process is lack of fusion, which is common for this material group [26,37]. While additional models can be implemented, the predictive model for lack of fusion is considered for the defect prediction before the process start, as it was used for the copper PBF process by Schäfle et al., which is based on the findings of Tang et al. [37,38]. This model supplements the system-based check of process readiness, as it is designed to support the planning stage of the process preparation. Possible additions to this model could address cracks, pores, and other types of insufficient adhesion [39,40].

After working through steps M1 to M8 for the models of the DT, requirements are determined and the system behavior is descriptively modeled. By using existing established models or drawing on empirical values or manufacturer specifications, the models used can be considered reliable and verified.

### 3.1.2. Sensors

In the study presented, the DT is not part of the PBF system from the outset, but is retrofitted. The condition and suitability of the existing sensors must therefore be considered within the framework of the methodology used. The following data is required for the models to be used and to create the conditions for the use of additional models:

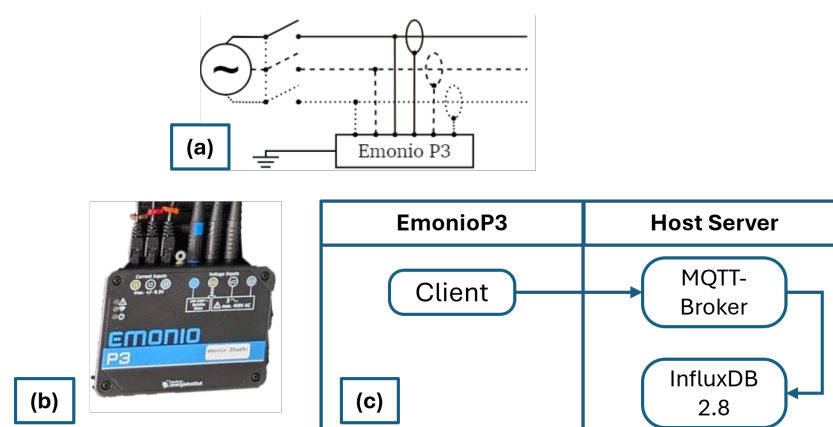
- Laser power
- Layer height
- Laser scanning speed
- Oxygen level
- Process chamber pressure
- Inert gas flow
- Status cooling system
- Cyclone filter differential pressure
- Electrical power consumption

With the exception of the electrical power consumption, all sensors necessary to acquire the data needed are already installed. The necessary implementation steps for sensors in DTs according to Fett et al. are therefore used on the example of the sensor for the determination

of the electrical power consumption, as this sensor needs to be retrofitted [4]. These steps comprise S1 to S7 in Figure 2. It is assumed that the sensor properties to be checked, such as accuracy, sensitivity, and measuring range, are suitable for the data collection for the DT. The sampling rate remains to be checked, as it is limited by the application programming interface (API). The selected models are used to assess whether the system is ready to start and to detect gross errors during the manufacturing process, which develop over the span of the manufacturing of several layers, providing a reaction time in the order of magnitude of minutes. A sampling rate of 1 Hz is therefore assessed as sufficient.

A three-phase power consumption with a total apparent power of 17.5 kVA at a voltage of 240 V relative to the neutral conductor must be measured. The control cabinet of the system is available as the measurement location. An integrated system with a wireless communication interface is desirable, as this limits the integration effort into the DT. In the control cabinet, the electrical supply of the PBF system is accessible, which allows for the measurement of electrical current via the induced magnetic field. This can be done by utilizing Rogowski coils, directly added around the electrical power lines. This poses a short measurement chain, reducing the possibility for errors. A device matching all given criteria and the preferred measurement technique, is the EmonioP3 by Emonio GmbH, Germany. This is an integrated device with network access and its own memory and enables measurements of 3-phase alternating current at 50/60 Hz with a voltage of 240 V against the neutral conductor and a current range of 2–4700 A, making it suitable for high-current measurements. The measurement accuracy is  $\pm 1\%$  for active power, apparent power, reactive power, current, and voltage. Sensitivity is not considered, as this is an integrated system and the target variables are already calculated by the built-in electronics.

The power sensor is mounted in the control cabinet on the contacts of the main switch. The sensor is powered directly via these contacts. The sensor is integrated into the existing lab intranet and connected to an MQTT broker. There, the read data is archived in an InfluxDB database. The database can be read via the Internet using an intranet-to-Internet gateway. An overview of the sensor integration is shown in Figure 6. The EmonioP3 sensor meets the requirements for sampling rate, ergonomics, accuracy, and measuring range. The degree of contamination in the environment is also not a problem for this sensor thanks to regular cleaning and controlled air purification.



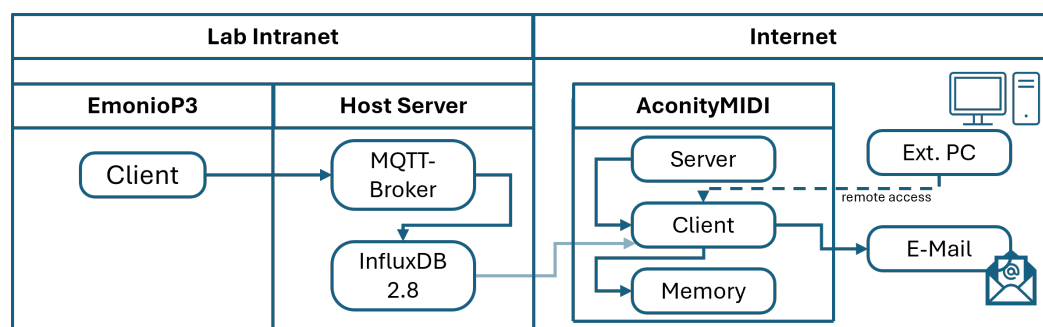
**Figure 6.** (a) Schematic representation of the electrical connection of the EmonioP3 sensor to the power supply of the PBF system under consideration, on the left a switchable AC source and the connections of the EmonioP3 to the three phases of the electrical current with Rogowski coils (as circles) for measurement, as well as the connection to the power supply of the device itself, which is also used for the determination of the voltage (b) Illustration of the EmonioP3 when connected, with three connections for power supply and voltage measurement and three connections for the Rogowski coils (c) Schematic representation of the network integration of EmonioP3, using an MQTT broker to store the data in an InfluxDB database.

The API of the AconityMIDI allows the measured values to be queried at a sampling rate of 4 Hz. This meets the requirement. The selected sensor technology is therefore considered verified. By working through S1 to S7 or the steps for sensors in DT, sensors and their respective data are analyzed and structured for further use, and the implementation of an additional sensor is prepared.

### 3.1.3. IT-Infrastructure

The IT infrastructure serves to integrate sensors and models, as well as data output. It comprises hardware in the form of the computing unit, memory, interfaces, and software for data processing, simulation, data archiving and transmission, and human–machine interaction [14]. The requirements for the IT infrastructure are developed based on Fett et al. and ISO 23247 [14,41]. Hardware requirements are derived from software requirements.

The software has to be compatible with multiple systems in different configurations. This enables transferability to other systems and the mapping of retrofits to the existing system. For the purpose of communication with users of the digital twin, a graphical user interface should be the central component of the software, which will display real-time process data and model calculation results. It should also be possible to send notifications to responsible persons outside the production site. This allows the software to meet the requirement for demand-oriented status queries and synchronization [41]. Interfaces with the sensor technology are necessary to collect the relevant data. The communication protocols used should be standardized and enable verification of the data exchange [41]. Communication should be possible with both the AconityMIDI and the external power sensor. The EmonioP3 sensor offers only network interfaces for real-time data communication, so a suitable interface must be provided for display via the dashboard. To make this possible, the network must enable local data exchange [41]. Both the power sensor EmonioP3 and the PBF-LB/M system AconityMIDI already have predefined interfaces for reading data, which is subsequently used. Figure 7 shows a schematic diagram of the IT infrastructure with the elements of the external EmonioP3 sensor, the AconityMIDI PBF system, and interfaces to peripheral entities, such as a separate PC or notification systems. The client assigned to the AconityMIDI represents the core of the DT: the software environment for data display and evaluation. The client is operated on the PBF system computer and receives data from the server, which consolidates data from the system's sensors and actuators. The client can receive data from the InfluxDB, which receives data from the EmonioP3 via the MQTT broker. It is possible to store Data in memory from the client. The client can communicate externally via email notifications in the event of process malfunctions, and access from external PCs is possible. On site or via external access, the client acts as a human–machine interface via its visualizations.



**Figure 7.** Schematic representation of the structure of the DT IT infrastructure, showing the connection of the external EmonioP3 sensor and the structure of the entities with Internet access.

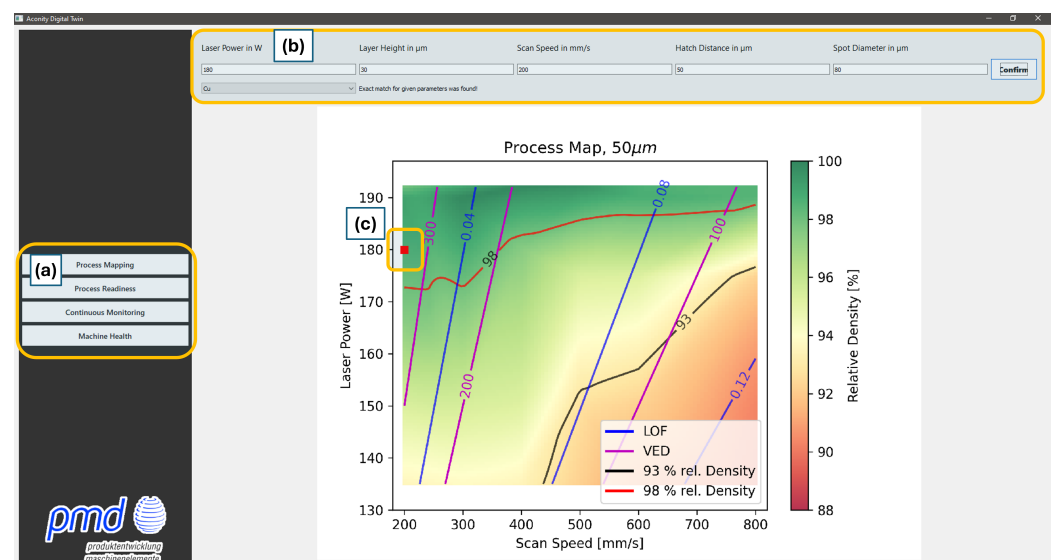
The IT infrastructure developed by working through I1 to I7 is the basis for the function of the DT together with surrounding systems. The flow of information between different entities is defined and structured.

### 3.2. Functions and Usability of the DT

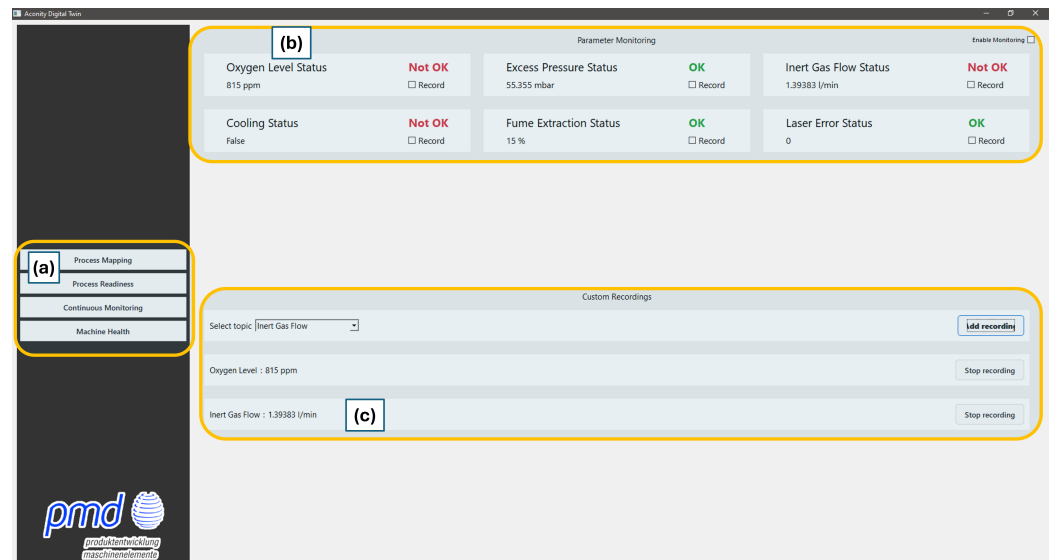
The main functions of the DT are accessible via buttons in the graphical user interface of the developed software. These are accessible via three buttons and are divided into “Process Mapping”, “Process Readiness”, and “Machine Health”. In addition, essential machine data in the window “Continuous Monitoring” is displayed that is otherwise only available in the user interface of the machine control system. This data is particularly relevant for location-independent process monitoring.

There is always a navigation field on the left side of the DT graphical user interface, as shown in Figure 8. The “Process Mapping” window shown in Figure 1 contains an input mask. This allows users to enter key process parameters that influence the volumetric energy density. In addition, users can select the material for which the probable relative density should be modeled. The process map displayed in the center visualizes the entered data on laser movement speed and laser power, allowing an assessment of the process range. The process model can be customized by selecting the material to be processed in the input mask. Process models created in the future can be integrated into the DT. How the process map shown and suitable material parameters were determined is described in the publication by Schäfle et al. [37].

In the “Process Readiness” window, status messages are displayed for the protective gas, the laser, the cooling system, and the pressure conditions in the process chamber in accordance with the models described in Section 3.1.1. Figure 9 shows in section (b) the various statuses relevant for process start-up, whereby the absolute sensor values are evaluated into OK/Not OK so that the operator can easily assess them. In section (c), individual data recordings can also be started. This is particularly useful in the event of process anomalies or experiments that involve influencing process conditions. This function is represented by the connection between the client and memory in Figure 7.

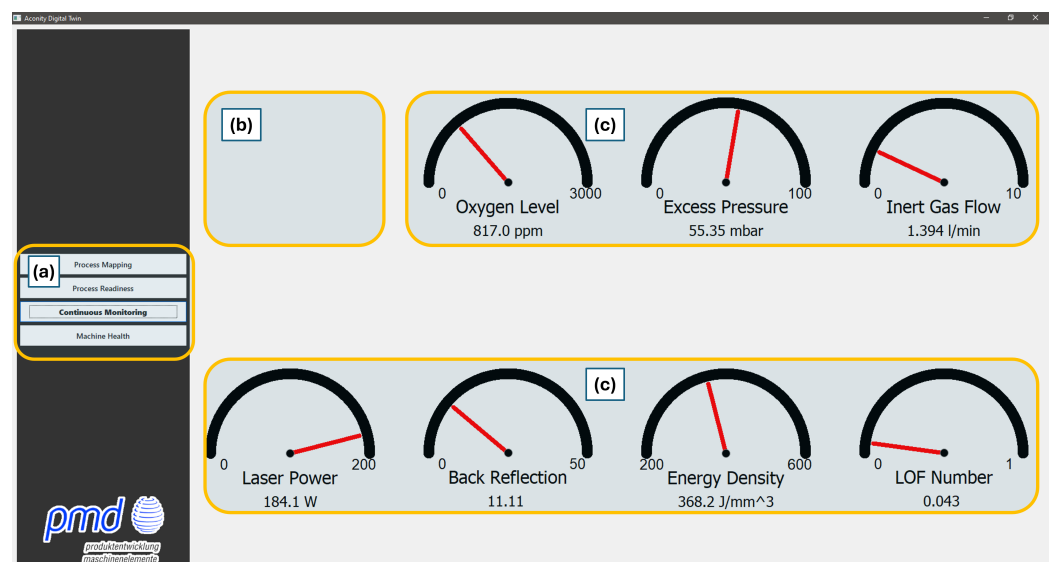


**Figure 8.** Process mapping window of the DT client with (a) navigation section to other windows of the client (b) input fields for process parameters and the process model to be used (c) the process map with an indicator of the process conditions which were put in and the expected relative density.



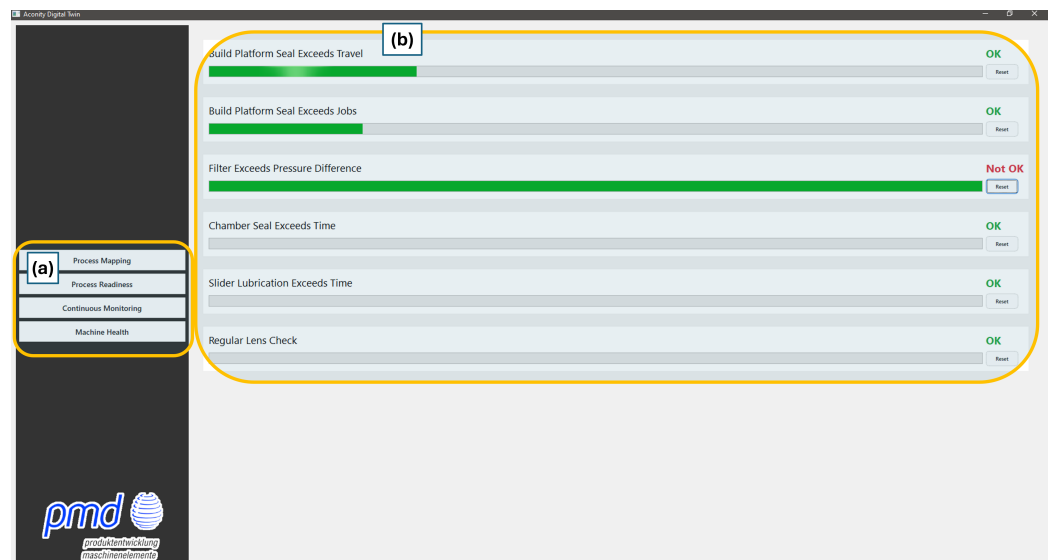
**Figure 9.** Process readiness window of the DT client with (a) navigation section to other windows of the client (b) an overview of the parameters necessary to assess before process start (c) the custom recordings section with the possibility to select parameters for data recording.

Figure 10 shows the “Continuous Monitoring” page of the DT user interface. This is mainly used to display sensor data, which can also be accessed in the plant control system. The transmission of unprocessed data is useful for remote access. In addition, the volumetric energy density achieved by the selected production parameters is automatically calculated and displayed, as is the dimensionless lack of fusion number. The determination of both variables is discussed in detail in the publication by Schäfle et al. [37]. Section (c) of Figure 10 shows that the display is in the style of a tachometer. Section (b) has been intentionally left blank and serves as a placeholder, for example, for the later display of calculated values based on the measured electrical energy consumption.



**Figure 10.** Continuous monitoring window of the DT client with (a) navigation section to other windows of the client (b) empty section space for the possible addition of a measured value display or a calculated value from a model, for example relating to electrical energy consumption or current manufacturing costs (c) display of sensor data or calculated values like the energy density and the LoF number.

In addition to the navigation area in (a), the “Machine Health” page in Figure 11 of the DT contains a display of the remaining service life of the monitored wear parts of the PBF system in section (b). As soon as a limit value is reached, the corresponding system component must be checked or replaced. Similar to Figure 9, inexperienced system operators in particular are supported, as abstract maintenance rules are presented in an easy-to-understand form and, at the same time, precise timing is possible, reducing the probability of errors even for experienced system operators. This applies in particular to the possibility of forgetting necessary checks or the reduction of manual tracking of maintenance dates.



**Figure 11.** Continuous monitoring window of the DT client with (a) navigation section to other windows of the client (b) overview of the condition of system components with a loading bar to show the elapsed service life of a specific component.

## 4. Discussion

Two key topics of discussion are how the implementation of the DT affects plant operation and how applicable the implementation methodology is. Another question that needs to be addressed is how the DT concept implemented to date can be further developed.

### 4.1. Implications of DT Functionality on System Performance

The implemented DT affects various aspects of the PBF system AconityMIDI, including but not limited to training new users, preparing and planning built jobs, and maintaining the system. The ability to specifically select process parameters and link them to a representation of the pore density that occurs increases the accessibility for the use of process models that were generated in previous studies. The preparation of CAD data and creation of the necessary data for the start of the process are directly supported by the parallel selection of process parameters for the desired component quality. A distinction can be made between a particularly high production speed or high quality in terms of relative density. This link between process models for copper PBF and a DT for operator assistance is new for the processing of copper or copper-based alloys. One notable source of error when starting up the system is compliance with certain parameters and the fault-free operation of the laser, which is supported by the DT. The demands on the operator are significantly reduced. After training, it is possible to work independently on the system much more quickly, which significantly reduces the workload of the supervisory staff. The display of system parameters, linked to calculated values indicating volumetric energy density and the lack of fusion number (LoF), which can also be accessed outside the laboratory

area, reduces the possibility of process errors, as system monitoring can be carried out as a secondary activity [37,38]. Only when anomalies occur does the operator need to leave their workstation and go to the system. The positive effects of using a DT therefore relate to organizational, technical, and business management aspects. Feasible tasks performed by system operators and supervisors are parallelized, making them more reliable in terms of results and significantly increasing the cost-effectiveness of plant operation. A quantification of the effects on the performance of the system under investigation is still pending. Since the PBF system under consideration is operated in a research context, production is frequently interrupted by experiments, modifications, and maintenance. One application of DT, namely the ability of newly trained system users to work independently more quickly, is immediately apparent, but is also difficult to quantify due to individual differences between people.

#### *4.2. Discussion of the DT Implementation Methodology*

The methodology for implementing DTs developed by Fett et al., which has already been successfully applied to other tasks, has also demonstrated its fundamental applicability to the PBF system under consideration. In view of the development that has taken place, there is potential for improvement that could be taken into account in the future adjustment of the methodology. The definition of the requirements for the behavior to be described should take place as an upstream step before the actual development of the system architecture so that research for the IT infrastructure and existing measurement chains can already begin. The reason for this is that the results of this work step can also influence the selection of models. The previous work step M1 for defining the requirements for the models can be retained and moved to after the definition of the behavior. This change allows for better control of the necessary modeling depth and enables preliminary considerations to be made regarding system design and the implementation of the IT infrastructure. In this study, this dilemma can be seen in the determination of the electrical input power. This is a variable that can be measured in many ways, with the selection of the measuring chain having a major influence on the post-processing of the data. On the one hand, current and voltage can be measured as discretized signals, and the phase shift and thus the active power can be determined. On the other hand, other physical effects can be used for measurement, or integrated sensor systems can be used to reduce the amount of data processing and thus the modeling effort. In particular, there could be potential for formal description using UML, as this allows system boundaries to be shifted across domains in order to expand the solution space. Semantic modeling languages such as UML and SysML are considered useful in other works as cross-disciplinary development tools [19,20], with UML in particular being used very successfully in a project on digital twins [19]. This also opens up possibilities with regard to the integration of sensors into the physical product, as integrated systems in particular must also be considered as an element of the IT system architecture. A cross-domain connection could also be established between the definition of the model structure and the identification of the hardware and software components. The reason for this is that the logical structure of the models directly influences the parallelizability of the calculations and thus the software architecture. When determining requirements and defining functions of the IT infrastructure, there is potential for simplification by taking into account existing architectures for digital twins, such as the ISO 23247 framework. These can also be used in the design of interfaces, with the open systems interconnection (OSI) model, for example, providing a well-communicated system for understanding and selecting network protocols [42].

There are comparable developments in methodological research that aim to support the implementation of digital twins [43,44]. In summary, however, it can be said that these

approaches are more difficult to apply to the selected task than the chosen methodology. The reasons for this relate to a wide variety of aspects. For example, there are approaches that focus only on sub-areas of DT implementation, such as models or sensors, which do not directly support a holistic approach. The level of detail of comparable methodologies may also be too high or too low. Too high a level of detail can make a methodology very helpful for a specific problem but, at the same time, reduce its transferability. Too low a level of detail may leave specific questions unanswered for a user. Another possibly problematic aspect is the wide variety of DTs. As expectations and tasks regarding a DT can vary, for example considering construction monitoring in comparison to PBF manufacturing, the used methodologies and the understanding of the necessity and importance of different tasks are changing, leading to methodologies or solutions emphasizing a specific aspect [45]. The chosen approach has proven its applicability on industrial transmissions and valves [4,46]. The high degree of dissimilarity of these examples underlines the practical value of the methodology. The resulting DT framework for the AconityMIDI PBF system is transferable to other machines at different plants, assuming that network connections and similar or identical sensors are available. Depending on the process materials, changes to the process model are necessary, but can be implemented.

#### *4.3. Directions for Further Research and Development*

The evaluation of data across a wide variety of data types using artificial intelligence or machine learning methods is becoming increasingly important and has reached a considerable level of maturity. This is especially interesting for the utilization in DTs, as the domains influenced by machine learning in AM are, for example, quality control and process optimization and ML is particularly suitable for analyzing large amounts of data [47]. The DT presented does not have integrated AI evaluation methods. The available camera images are not yet being used, but this represents an important approach, especially for defect detection or the preemptive monitoring of the powder bed after recoating [48]. Automatic or manual control options via the DT are one way of greatly increasing functionality. In the event of errors such as severe component distortion, which can result in a collision with the powder coating applicator, automatic or manual intervention could offer enormous potential for preventing a process from being interrupted or parts and system components from being destroyed [49]. The combination of process monitoring techniques and process control is being explored extensively in recent years [50]. The aspect of sustainability gains more and more attention [51]. Not only in the sense that the reduction of environmental impacts of the manufacturing industry is viewed as pivotal, but also because environmental impacts are inherently linked to costs and therefore the sustainability of business models. Utilizing a DT supports the determination of indicators regarding the costs of production or the produced carbon dioxide equivalent per part produced [52].

The open architecture of the DT allows for further development, which can be carried out in particular by incorporating experience gained from the initial and ongoing use of the current system. ISO 23247, which highlights the need for implementing an open and flexible system architecture, is therefore considered.

## **5. Conclusions**

In the presented study, a digital twin is implemented for a PBF system, which is used for the challenging processing of copper materials. The implementation is carried out consistently in line with a methodology developed by Fett et al. Models, sensors, and the IT infrastructure of the DT are described, and the user interface of the DT client that has been set up is presented, along with the effects on the use of the PBF system. The most important results of this study can be summarized as follows:

- The implemented DT has a comprehensive impact on plant operation. It simplifies the training of new operators, facilitates process planning and the use of process knowledge, and increases process stability through reliable tracking of the service life of critical components. Above all, it improves the ergonomics of use by simplifying information processing and storage for system operators.
- The methodology used has proven itself and its applicability has once again been evaluated with positive results. The order in which the work steps are carried out could be adjusted with regard to requirements gathering. A more cross-domain consideration between the definitions of models and existing hardware and software is considered useful, as the logical structure of models and the parallelizability of calculations depend directly on the structure of the system under consideration.
- The implemented DT is, according to the authors, only a basic version that is capable of running, but its range of functions has a noticeable impact on operations and meets the specified requirements to the planned extent. The planned use of EmonioP3 will open up further areas of application for the DT in the future, particularly for sustainability assessments and cost calculations, which will require the integration of additional models. AconityMIDI can be integrated even more deeply into the DT by using all sensors or camera images together with artificial intelligence-supported image evaluation for fault detection and general process monitoring.

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## Abbreviations

The following abbreviations are used in this manuscript:

|          |                                                  |
|----------|--------------------------------------------------|
| DT       | Digital Twin                                     |
| PBF-LB/M | Powder Bed Fusion, using a Laser Beam for Metals |
| AM       | Additive Manufacturing                           |
| TQM      | Total Quality Management                         |
| TDABC    | time-driven activity-based costing               |
| UML      | Unified Modeling Language                        |
| SysML    | Systems Modeling Language                        |
| OSI      | Open Systems Interconnection                     |

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