Lean Production to Increase Reproducibility and Work Safety in the Laser Beam Melting Process Chain

C. Bay, A. Mahr, H. Groneberg, F. Döpper

***Abstract*—**Additive Manufacturing processes are becoming increasingly established in the industry for the economic production of complex prototypes and functional components. Laser beam melting (LBM), the most frequently used Additive Manufacturing technology for metal parts, has been gaining in industrial importance for several years. The LBM process chain – from material storage to machine set-up and component post-processing – requires many manual operations. These steps often depend on the manufactured component and are therefore not standardized. These operations are often not performed in a standardized manner, but depend on the experience of the machine operator, e.g., levelling of the build plate and adjusting the first powder layer in the LBM machine. This lack of standardization limits the reproducibility of the component quality. When processing metal powders with inhalable and alveolar particle fractions, the machine operator is at high risk due to the high reactivity and the toxic (e.g., carcinogenic) effect of the various metal powders. Faulty execution of the operation or unintentional omission of safety-relevant steps can impair the health of the machine operator. In this paper, all the steps of the LBM process chain are first analysed in terms of their influence on the two aforementioned challenges: reproducibility and work safety. Standardization to avoid errors increases the reproducibility of component quality as well as the adherence to and correct execution of safety-relevant operations. The corresponding lean method 5S will therefore be applied, in order to develop approaches in the form of recommended actions that standardize the work processes. These approaches will then be evaluated in terms of ease of implementation and their potential for improving reproducibility and work safety. The analysis and evaluation showed that sorting tools and spare parts as well as standardizing the workflow are likely to increase reproducibility. Organizing the operational steps and production environment decreases the hazards of material handling and consequently improves work safety.

***Keywords*—**Additive manufacturing, lean production, reproducibility, work safety.

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I. Introduction

THE individual steps in the LBM process chain differ greatly in terms of duration, complexity and their influence on component quality. The reduction of the reject rate or the production of high-quality components is time-consuming and cost-intensive and requires a high level of process and technology expertise [1]-[3]. This is also reflected in the conflict between the target variables of time, quality and costs [4]. Users of LBM process are faced with the challenge that consistent component quality is rarely a given, even with repeated production [5]. The resulting lack of process stability and reproducibility leads to a high reject rate as well as a high technical and financial investment to ensure the required quality. This in turn means there is a high threshold to overcome in order for the potential of LBM to be exploited. This is particularly evident for small and medium-sized enterprises (SMEs) [5]-[7]. Furthermore, Additive Manufacturing processes often do not have the robustness and process capability relevant for quality assurance required in industry – there is insufficient process transparency [8]-[10]. The quality reproducibility of additively manufactured components is reduced by the susceptibility to disturbance variables such as temperature and humidity fluctuations or insensitivity to operating errors [2], [3], [9], [11], [12]. Ensuring reproducibility is considered one of the core tasks and a critical success factor for the industrialization of Additive Manufacturing [7], [8], [13]. This has to be addressed technically and technologically on the machine and process level, but also organizationally and internally with a strategic focus.

In addition to the lack of process transparency in LBM, users of Additive Manufacturing often have little experience and expertise specific to the process and process-chain in terms of the creation, implementation, and maintenance of work safety concepts [14]. Omitting operational steps means increasing the risk for the machine operator. Work steps that are not primarily quality-relevant but have an impact on the service life of the machines are performed irregularly. An example of these operational steps is the execution of regular maintenance procedures. Sporadic operational steps, such as filter changes or plant conversions, pose a high hazard [15]. The challenges of improving the reproducibility of component quality and work safety vary in the individual work steps. This paper examines the challenges regarding their influence on reproducibility and work safety using selected criteria for the entire LBM process chain. These challenges are to be met by standardization and the avoidance of errors, following the guiding principles of the Lean Production approach. The potential for standardization and Lean Production is particularly high in SMEs [16]. The 5S method is therefore applied to derive corresponding solution approaches in the form of recommended actions, and will be evaluated in terms of their implementation effort and their potential for increasing reproducibility and work safety. The development and evaluation of the solution approaches for improving work safety and for reducing the hazards for plant operators is based on the hazards that the materials entail as well as the German standards, guidelines, and technical rules for hazardous substances.

II. State of the Art

The business objective of every company is to reduce costs and increase economic revenues. One of the levers for reducing costs in production is the minimization of non-value-added processes and thus the minimization of waste. The principles and methods of Lean Production incorporate this objective. Large companies in particular have been using Lean Production for many years to design their processes [17]. In the "ecosystem" of Additive Manufacturing, the improvement of processes, process chains and production is not usually achieved through the methodical application of these Lean approaches [18], [19].

The goal of the 5S method is to ensure the reproducibility and thereby the detachment from the individual execution [20]. The systematic approach makes it possible to design workplaces, working environments and processes sustainably, locally and cleanly. Learning processes and training can be made more effective and efficient [17]. The 5S method can support work safety and health protection by supplementing the STOP principle which is fundamental to work safety [21]. The following steps are included in the continuous cyclical improvement process of the 5S method [22]:

1. *Sort:* Sort all items and remove the unnecessary ones.
2. *Set in order:* Design an ergonomic and structured working environment.
3. *Shine:* Clean and inspect the working environment.
4. *Standardize:* Create standards through labels, markings or cleaning plans.
5. *Sustain/Self-discipline:* Ensure the application of the 5S methodology.

The goal of Poka Yoke is the detection, analysis and regulation of random human error [23]. Processes that are not very robust must be protected from these errors in order to ensure reproducible product quality that complies with standards [24].

Additive Manufacturing is developing into an industrial manufacturing technology. Currently, LBM is the most widely used Additive Manufacturing technology for metallic components [25]. The starting materials for LBM are metal powders, which are classified as inhalable and alveolar due to their particle size distribution [26]. Specific threshold values of the maximum acceptance and tolerance concentration apply [27]-[30]. In addition, common low-density metal powders such as titanium, aluminium and their alloys are reactive. As a result, a dispersion of metal powder, especially without the use of effective countermeasures could cause a dust explosion [31]. A large number of metal powders, such as steels or other alloys containing nickel, has a toxic effect. Alloy components that are carcinogenic, mutagenic or reprotoxic (CMR) are particularly hazardous to health [28]. Therefore, a concept of risk-related measures according to TRGS 910 is required for activities with CMR substances [30], [32], [33]. The technical guideline of the Association of German Engineers (VDI) 3405 part 6.1 "User Safety in Additive Manufacturing – Laser Beam Melting of Metals" contains general recommended actions for typical and sporadic operational steps to reduce the hazards, particularly of reactive and toxic metal powders [15]. However, these recommended actions must be adapted to the company-specific framework conditions and process chains, and then implemented in concrete terms [31]. The creation, compliance and continuous adaptation entails a great deal of effort for companies due to a lack of internal and external experience and expertise [14].

III. Approach and Methodology

By applying the 5S Lean methodology, the LBM process chain can be equipped with a variety of solutions to increase reproducibility and work safety. The first step is therefore to identify the operational steps with the greatest influence on reproducibility and work safety. All LBM steps are divided into the following process categories and their influence on the reproducibility of the component quality is determined, based on selected criteria (Table I).

A. Operational Steps When Entering and Leaving the Workspace

This category covers: putting on and removing personal protective equipment (PPE), the inspection of safety devices such as gas sensors and inert gas supply, as well as ventilation equipment. For example, if the ventilation system, in addition to achieving the required air exchange rate, also has the function of maintaining the required climatic conditions, it can also influence the reproducibility of component quality.

B. Process Specific Operational Steps at the LBM-Machine

The process specific operational steps that are associated with the LBM-machine are usually performed with the door of the LBM machine open or by gloved intervention. When handling metal powder, one must connect the machine operator to the equipotential bonding of the LBM plant. Removing powder from the panel where the manufactured components are, the removal of the components and the filling of new metal powder all have a high influence on work safety [31]. The reproducibility of component quality is particularly influenced by the insertion and referencing of a new build plate, the levelling of the coater as well as the cleaning of the laser protection glass and the inerting process [34], [35].

C. Process Specific Operational Steps at the Peripheral Devices

The peripheral, process-specific operational steps include all additional activities in preparation for the manufacturing process as well as for the post-processing of components. With the exception of powder reprocessing using sieves, these steps have a comparatively low influence on work safety as a smaller amount of powder is handled. In contrast, digital job preparation, the removal of supporting structures and application-specific post-processing have a stronger influence on the reproducibility of component quality.

D. Sporadic Operational Steps

These steps in the LBM process chain, which are detached for direct component production, are required to ensure the cleanliness and maintenance of the function of all systems and peripheral equipment. Due to their sporadic nature and contact with metal powder and waste products, these steps have a high impact on work safety, whereas the reproducibility of component quality is mainly influenced by regular maintenance.

The criteria are based on the Failure Mode and Effects Analysis, FMEA [36]. The evaluation of work safety only considers the process-specific hazards, particularly those arising from the metal powder. The arrangement of the steps is not based on the general LBM process chain for producing components, but on the typical workflow of a machine operator from entering to leaving the workspace.

TABLE I
CRITERIA FOR EVALUATING THE INFLUENCE OF WORK STEPS ON REPRODUCIBILITY AND WORK SAFETY, BASED ON [36]

Reproducibility	Work safety
Probability of the occurrence of a quality-related faulty execution	Probability of the occurrence of hazards
Extent of quality-related faulty execution	Extent of direct and indirect hazards
Probability of the detection of a quality-related faulty execution	Probability of detection of hazards potentials

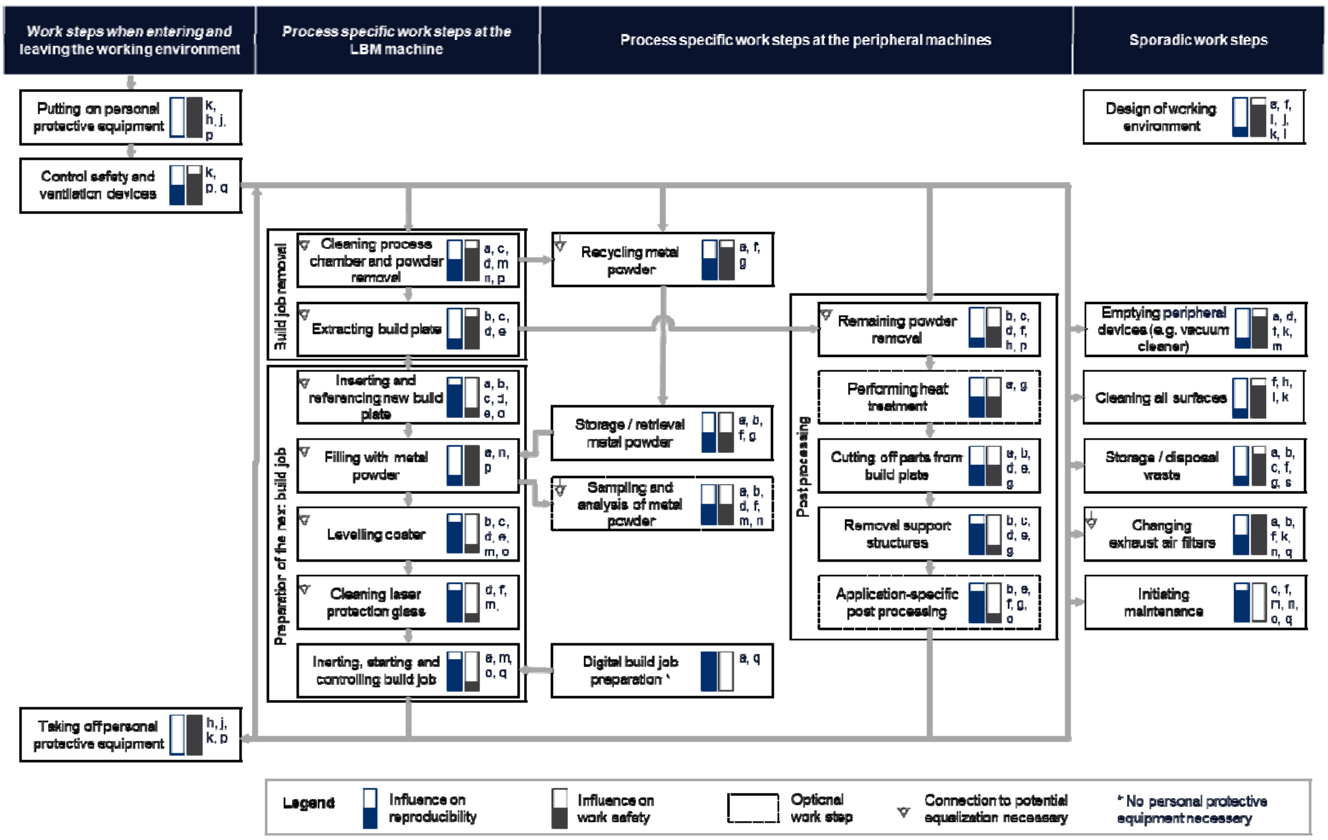

Fig. 1 Exemplary workflow in the context of component manufacturing using LBM

IV. DERIVATION OF SOLUTION APPROACHES BASED ON 5S

By applying the 5S method to the LBM, all operational steps are ideally designed in such a way that they can be carried out safely and reproducibly, under different framework conditions and irrespective of the machine operator and his/her concentration levels. The following solution approaches serve as general recommended actions, which have to be adapted based on the company-specific conditions. These recommended actions take into account the work safety standards of VDI 3405 part 6.1. The influence of these recommended actions on the individual LBM operational steps is shown by a corresponding reference in Fig. 1. Their applicability and influence depend on the type of LBM system and the peripheral equipment. The solution approaches are evaluated in terms of the effort involved in their implementation and their potential to increase reproducibility and work safety.

A. Sort

Reduce the Number of Metal Powder Alloys (a)

The hazards and quality requirements for LBM depend on the different metal powder alloys. By reducing the number of processed metal powder alloys, the costs for segregation of storage, the manual effort involved in changing materials and the risk of mix-up or cross-contamination of metal powders can be reduced.

Reduce the Number of Specific Tools/Items (b)

Users of LBM typically have no experience of the application-specific tooling requirements when they start implementing an LBM process chain and often use standard toolsets. A large proportion of the tools contained in these toolsets is usually never needed. These tools should be separated out to structure the working environment. For example, it is sufficient to keep only the matching Allen keys close to the system. This applies in particular to the tools for fixing and releasing the build plate or for levelling the coater. Alternatively, special tools can also be avoided by storing only tools that are universally applicable.

B. Set in Order

Group Tools and Spare Parts (c)

Only a small selection of tools is required for different steps. Tools and spare parts should therefore provide in groups according to the workflow (e.g., cleaning, set-up, disposal).

Define Storage Locations for Tools and Spare Parts Where They Are Needed (d)

Due to the high geometrical freedom of the components that are possible with LBM, new special tools are required. These can often be borrowed from other work areas. To make them retrievable, tools have to be assigned to a fixed place. One means of doing this is to use foam inserts. This also applies to disposable PPE (e.g., gloves). Furthermore, the tools must be stored close to the place where they are needed. For example, attach Allen keys for (dis)mounting the build plate directly next to the system (e.g., with a magnet on the shadow wall).

Label Name and Purpose of Tools and Spare Parts (e)

To support inexperienced machine operators, tools must be provided with the correct designation and the respective function. For example, the corresponding screws must be assigned to the different sizes of Allen keys.

Organize the Workspace in Terms of Frequency of Machine, Tool and Spare Parts Usage (f)

In the case of particularly sporadic steps, such as maintenance or filter change, there is a danger of confusion in the choice of the tools and spare parts required. Therefore, sporadically required tools and spare parts should not be stored in the primary workspace. To prevent further errors, transport should be minimized. Unnecessary movements increase the risk to employees, which is why a reduction should be pursued here. Other Lean methods such as the spaghetti diagram and value stream design can support this process by optimizing the factory layout.

C. Shine

Enable Near-Emission Absorption of Waste and Residual Materials (g)

According to VDI 3405 part 6.1, airborne emissions from the use of machines and peripherals and, in general, from handling the metal powder must be collected close to the emission source [15]. This can be realized for example by a mobile wet separator. Other waste and residual materials must also be collected directly at the place of origin [37].

Minimize Powder Carry over into Other Workspaces (h)

Metal powders can be carried over into other workspaces as dust in the air or by adhering to components or work clothing. To reduce the exposure space for metal powder, all open handling steps of metal powder must be physically separated. In addition, the metal powder must be thoroughly cleaned off of components manufactured via LBM before performing internal and external logistics processes. Work clothing must also be confined to the workspace and cleaned regularly. Another means of reducing powder carryover is the use of dust mats at the access doors.

Visualize the Deposition of Metal Powder (i)

Due to open powder handling and residual powder in the components, powder can settle on horizontal surfaces in the work environments in particular (e.g., floor, peripheral surface). A high light/dark contrast between the surface and the powder allows the visualization of the powder deposition and facilitates cleaning routines [37].

Define and Mark Workspaces with Special Requirements for PPE (j)

CMR metal powders in particular entail high standards of employee protection. These requirements can often only be met by the use of PPE in accordance with the STOP principle. Working environments that may only be entered wearing PPE must be separated and marked. Furthermore, access without PPE can, for example, be avoided by the use of technical means such as checking the electrostatic discharge capacity of a person before entering the working environment (application of the Poka Yoke method).

Establish a Fixed Cleaning Schedule (k)

The capacity utilization of the LBM machines as well as of the employees varies depending on the requirements of the components or the order situation. As a result, cleaning processes are often postponed or neglected. Therefore, fixed cleaning schedules have to be determined with responsible employees. For CMR materials, it is particularly important to store leisure and work clothing separately [37]. Especially in this case, cleaning schedules must include not only the cleaning of the working environment but also the changing or cleaning of work clothes.

Simplify Cleaning Procedures (l)

Metal powders are deposited from the air on horizontal surfaces in particular. Especially rough surfaces and undercuts are difficult to clean. For this reason, smooth and easily cleanable surfaces should be provided when designing the working environment to ease cleaning and lower the threshold for cleaning. For example, open-pored foam inserts increase the amount of cleaning involved. By choosing coated foam inserts, cleaning can be reduced.

D. Standardize

Standardize the Workflow with the Use of Checklists (m)

To standardize the general workflow and reduce the challenges regarding the reproducibility of component quality and work safety, checklists, standard worksheets or job sequence cards can be used analogously to other manufacturing areas [22].

Standardize the Workflow by Numbering (n)

This approach combines the aforementioned approaches (e) and (k). This means that not only the objects and their storage location are labelled and a checklist is created, but all tools and consumables and their storage location are numbered according to the order of their use. This lowers the threshold for their use. In addition, different types of steps can each be described by a numbering sequence and distinguished from one another by different colour markings. This minimizes unintentional omissions of work steps, while also easing new employee training, and increasing reproducibility. The implementation of and compliance with organizational protective measures is also possible. However, this approach can only be used to a limited extent, for example in the step "Removal of support structures", since the selection and sequence of the required tools is strongly dependent on component geometry and component-specific requirements.

Provide Additional Information (o)

The provision of additional information can be particularly helpful when performing sporadic operational steps or training new employees. For example, this can take place over smart devices or hand scanners, which make possible to gather additional information from databases. In addition to operating instructions, short videos can also be made available to visualize operational steps directly at the workstation.

Avoid Omitting Safety Relevant Work Steps (p)

When employees forget to connect to the equipotential bonding, they are endangering themselves. This can be avoided by using the Poka Yoke method. For example, the LBM machine and the periphery can be designed in such a way that it can only be opened or used when an antistatic wrist band is applied. This can be achieved by using a capacitive/ inductive sensor at the connection to the equipotential bonding. A further example is to couple the function of the air conditioning system with the LBM system or other peripherals, which means that they can only be used when the air conditioning system is functioning properly.

Use Digital Technologies to Reduce Inhibition Thresholds (q)

The use of checklists to standardize the workflow is easy to implement. However, there is a risk that they are not used as much in the daily routine out of convenience. This can be circumvented by using digital technologies, for example, by displaying the workflow on dust-protected screens or smart devices that are operated with gloves or by means of gesture/ voice control.

E. Sustain/Self-discipline

Establish a Continuous Improvement Process (r)

In the context of this work, the 5S methodology was used to derive solutions to ensure work safety and increase reproducibility. For the sustainable success of these approaches, the methodology should be applied cyclically and continuously to achieve a sustainable optimization of the production. Methods such as the Deming/PDCA cycle can be used for this purpose [38].

Standardization of Organizational and Infrastructural Company Interfaces (s)

The sustainable increase in the degree of standardization affects general company procedures along the entire manufacturing process. The transfer and provision of the right information, the design of procedures and operational steps and the correct handling of materials are central standardization elements of a company. One example is company-wide waste disposal management system. Standards for the disposal of hazardous powders, auxiliary materials and contaminated liquids can be transferred into a holistic production system and defined as a generally applicable guideline.

To prioritize the implementation of the solutions and approaches described here, the potential and benefits for increasing the reproducibility and work safety can be juxtaposed with the implementation effort and costs. Fig. 2 shows the comparison and evaluation.

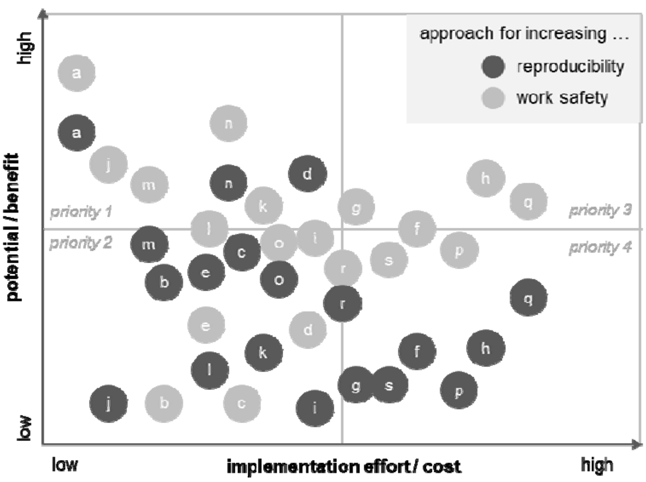

Fig. 2 Evaluation and prioritization of the derived solution approaches

V. Summary and Outlook

This paper focuses on analysing all steps of the entire LBM process chain based on the typical workflow of a machine operator. The operational steps are evaluated regarding their challenges in terms of part quality reproducibility and the hazards resulting from handling metal powder. The organizational steps regarding the production environment, the steps regarding the LBM machine and the peripheral devices and the sporadic steps of cleaning and maintenance have been analysed based on a holistic process chain perspective. The Lean methodology has been used. The application of these approaches ensures work safety and increases reproducibility within the scope of quality management on an organizational level for the entire LBM process chain. Sorting tools and spare parts as well as standardizing the workflow are likely to increase reproducibility. Organizing the operational steps and production environment decreases the hazards of material handling and consequently improves work safety. These approaches were prioritized according to the effort involved in their implementation in relation to the expected benefit for increasing reproducibility and work safety.

The cyclical implementation and verification of the 5S methodology are necessary since the innovative nature and the progress of the processes and process chains of Additive Manufacturing are estimated to be very high. To further increase component quality, ensure process stability and productivity, methods and tools of quality management must be applied on a process-related and production-technology level and adapted to the requirements of Additive Manufacturing and its process chains.

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