Automation in Laser Powder Bed Fusion: A Literature Review of Process Fundamentals and Automation Potential

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Preface

The purpose of this literature study is to gain initial knowledge on the current status of additive manufacturing, more specifically laser powder bed fusion manufacturing. The study's findings are compiled as conclusions about the challenges and general knowledge, deemed usable as a foundation in a project aiming towards partially automating the design process of components, that is part of the Advanced Project Course TMPM03/TMPM05, given at Linköping University.

Contents

1 Introduction

To effectively research and develop an area of science, first one must obtain the prior knowledge of the field in order to expand upon it. One excellent way of doing this is with a literature study, which is the path of this project. The following chapters will detail the methodology used for the literature study, the scope of the study as well as the results that came from it.

2 Literature Study

2.1 Methodology

For a literature study to be successful it is imperative that it is performed in a structured and well-defined way, to avoid biases and missing information. The method used for this literature study is one initially developed for software engineering by Kitchenham and Charters [1], although it fits this project just as well. The process of using this method can be summarized as a few bullet points:

1. Define scope (research questions)
2. Create a review protocol with keywords, databases and inclusion criteria
3. Search systematically across several databases if available (divide the research questions between group members)
4. Screen the results
5. Report findings and relate to research questions

2.2 Scope (Research Questions)

In this section the scope of the literature study is presented as a bullet point list consisting of all the research questions this study aims to answer. The responsible member(s) are displayed within parentheses after each question.

1. How does the powder bed fusion manufacturing process work?
2. What are support structures and what effect does printing orientation have on product characteristics?
3. What are the main problems in the powder bed fusion manufacturing process currently?

4. What does the design process look like from initial idea to final product?
5. Which software are used within the problem domain and which of them are Python compatible?
6. How can Python be used to solve some of the problems of the current process?
7. How does integrating python script with current tools used for DfAM/L-PBF work?
8. What design methods exist currently and how do they work?
9. What type of components are generally manufactured with L-PBF?
10. What does a typical testing standardized component look like in AM?

2.3 Keywords, Databases & Inclusion Criteria

To keep the search organized and structure several keywords are defined, these are used to search for articles and other literature on the different databases. The databases and search engines used are also presented for transparency. This study uses the simple inclusion criteria that the literature should be relevant to the subject and no older than 20 years, preferably 10. Below is two list containing the keywords/key phrases and the databases used for the study.

Keywords:

- Powder bed fusion Additive manufacturing
- Python programming with Additive Manufacturing
- Lattice design
- Generative design
- Topology optimization
- Powder bed fusion print simulation
- Powder bed fusion supports
- Additive manufacturing design software

- Additive manufacturing design methodology

Databases and search engines used in the literature study are:

- Google Scholar
- Scopus
- IEEE Xplore
- ACM DL

2.4 Literature List

The literature review aims to draw meaningful conclusions and compile a comprehensive list of references. A wide range of articles and other relevant sources will serve as the foundation for the project, informing key design decisions. The complete list of referenced literature is provided in the references section on page 17.

2.5 Results

1. **How does the Laser Powder Bed Fusion manufacturing process work?**

   All powder bed fusion methods in AM have some components in common; Some type of thermal source to induce fusion of the powder particles, a way of controlling where in each layer the fusion occurs and a way of adding more powder for the next layer [2]. In the case of laser sintering powder bed fusion (LS PBF) machines, as the name suggests, the method of inducing and controlling fusion is with the help of a controllable laser. The working order of a typical LS-PBF machine can be described as [2]:

   (a) Pre-heating of the build plate and area to a temperature slightly below the melting temperature of the powder
   (b) Application and smoothing (often with a roll) of the first powder layer (0.075-0.1 mm thick)
   (c) Laser is applied to induce fusion of the powder in desired areas to create a slice of the designed cross-section
   (d) The entire build plate shifts downwards by one layer thickness

(e) Loop back to b) and repeat until component has been formed
(f) Removal from the build plate after a cool-down period to avoid warp due to uneven thermal contraction
(g) Removal of excess powders and other finishing operators are performed

2. **What are support structures and what effect does printing orientation have on product characteristics?**

Support structures are effects of the additive manufacturing process. They are necessary for the complex geometries that additive manufacturing make possible. As the complexity of the component increases, chances increase that some kind of support structure is needed. For instance, with so-called “overhangs”, support structures are often needed. Support structures increase the time, material needed and therefore cost of the total process. They also introduce the amount of manual intervention needed in an otherwise largely automated process, and the removal of support structures can damage the component itself. Therefore, it is important to decrease the number of support structures needed. Some components can easily be optimized for additive manufacturing by moving or rotating the component itself. For instance, a simple T-shape needs support structures under both overhangs if printed upright. Turning the shape on its head instead means no support structures are needed at all. The biggest downsides of support structures are:

- The removal of support structures requires manual work.
- Support structures constraint geometries of the component because they need to be able to be accessed by a tool or hand.
- They result in wasted material.
- They add printing time and cost.
- The removal of support structures can damage the finish of the component.
- The design file itself requires more time, effort, data transfer and space.

Support structures can be divided into two different ”regions”, these being the support comb and the support body [3]. The support combs going "in" to the part in order to improve the support's connection to the part and to reduce surface roughness. The support body has several functions like providing a heat transfer path from body to build plate and supporting overhang areas during cooling. The effective dissipation of heat have been observed to reduce residual stress in the part, delamination of layers and improve micro-structural properties. The negative part about the support structure is that it generally adds a substantial amount of material and print time, so it would be desirable to only use just as much support structure as required.

According to Aiza , I. et al [4] the build orientation has a big impact on things like dimensional accuracy, physical parameters, micro structural and mechanical properties. For example surface roughness and porosity generally increases with build angle, while in the case of static strength there is no consensus on the build angle effect.

3. What are the main challenges in the powder bed fusion manufacturing process currently?

As in any field, there are problem areas within L-PBF manufacturing. A general limitation of the method is the size of products that can be created. A rule of thumb is that only components considered small are feasible to print, since larger ones are more time consuming and therefore more costly to produce [5].

Designing a product for printing requires working in a geometric CAD environment, which is later linked to programs for build preparation and production simulation before the part is manufactured physically. This workflow is often regarded as labor intensive due to the need to switch between several programs, perform file format conversions, and maintain thorough file management. As a result, a parameter change discovered during the later stages of simulation may force the designer to return to the original CAD geometry and repeat adjustments across the following steps. In addition, repeated file exports and format conversions risk compromising data integrity, which can affect the quality of the final outcome [5].

According to one author, one of the problems with SLM (Selective Laser Melting) specifically is the lack of reliability and quality in regard to dimensional accuracy, strength and surface roughness. The outcome of Selective Laser Melting depends on the parameters of the process, as well as the interplay of physical phenomena in the material itself. These issues result in challenges with reproducibility and repeatability, which means that mass production becomes more difficult. These issues can be seen when examining the standard deviation of components in their tensile strength and elongation compared to the standard deviation of traditional manufacturing methods.

4. What does the design process look like from initial idea to final product?

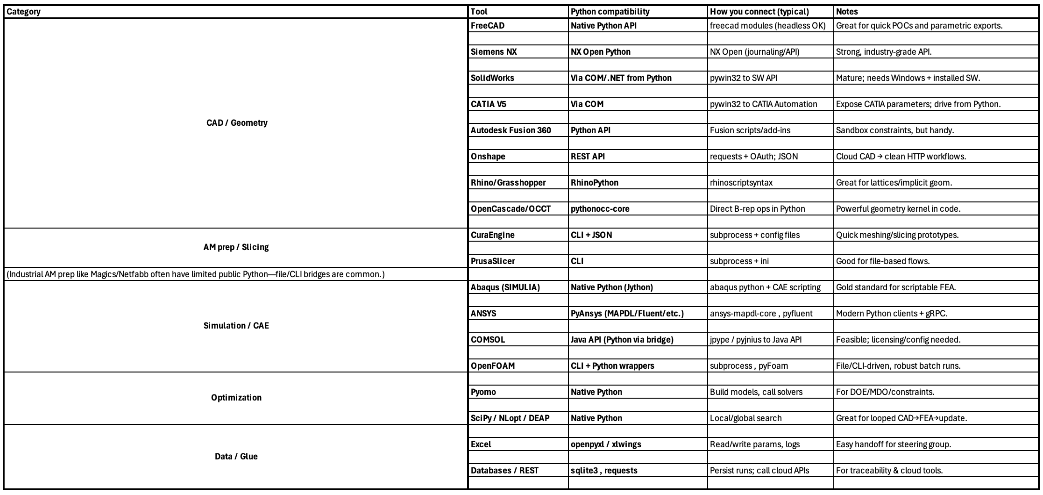
To explain the process in a simple way K.V. Wong & A.Hernandez [6] used a figure to show that the process follows the following flow:

(a) Design Concept(s)
(b) Parametric Design (CAD tool)
(c) Analysis & Optimization (CAE tool)
(d) Rapid Prototyping
(e) Final Design

In addition to this it can be relevant to add the ”slicing” and AM preparation step after analysis, since this is an important part of the process that prepares the part for printing by dividing it into the printable ”layers” [7].

5. Which software are used within the problem domain and which of them are Python compatible?

The design and manufacturing process within Laser Powder Bed Fusion (L-PBF) typically involves several software tools across different stages: Computer-Aided Design (CAD), build preparation, simulation, and optimization. Common CAD programs include CATIA, SolidWorks, Siemens NX and FreeCAD, while build preparation is often handled in tools such as Magics, Netfabb or Cura. Simulation and verification of stresses, thermal behavior and distortion are usually performed in software like ANSYS, Abaqus or COMSOL. Optimization and process



Category	Tool	Python compatibility	How you connect (typical)	Notes
CAD / Geometry	**FreeCAD**	**Native Python API**	freecad modules (headless OK)	Great for quick POCs and parametric exports.
	Siemens NX	**NX Open Python**	NX Open (journaling/API)	Strong, industry-grade API.
	SolidWorks	**Via COM/.NET from Python**	pywin32 to SW API	Mature; needs Windows + installed SW.
	CATIA V5	**Via COM**	pywin32 to CATIA Automation	Expose CATIA parameters; drive from Python.
	Autodesk Fusion 360	**Python API**	Fusion scripts/add-ins	Sandbox constraints, but handy.
	Onshape	**REST API**	requests + OAuth; JSON	Cloud CAD → clean HTTP workflows.
	Rhino/Grasshopper	**RhinoPython**	rhinoscriptsyntax	Great for lattices/implicit geom.
	OpenCascade/OCCT	**pythonocc-core**	Direct B-rep ops in Python	Powerful geometry kernel in code.
AM prep / Slicing	**CuraEngine**	**CLI + JSON**	subprocess + config files	Quick meshing/slicing prototypes.
	PrusaSlicer	**CLI**	subprocess + ini	Good for file-based flows.
(Industrial AM prep like Magics/Netfabb often have limited public Python—file/CLI bridges are common.)				
Simulation / CAE	**Abaqus (SIMULIA)**	**Native Python (Jython)**	abaqus python + CAE scripting	Gold standard for scriptable FEA.
	ANSYS	**PyAnsys (MAPDL/Fluent/etc.)**	ansys-mapdl-core , pyfluent	Modern Python clients + gRPC.
	COMSOL	**Java API (Python via bridge)**	jpype / pyjnius to Java API	Feasible; licensing/config needed.
	OpenFOAM	**CLI + Python wrappers**	subprocess , pyFoam	File/CLI-driven, robust batch runs.
Optimization	**Pyomo**	**Native Python**	Build models, call solvers	For DOE/MDO/constraints.
	SciPy / NLopt / DEAP	**Native Python**	Local/global search	Great for looped CAD→FEA→update.
Data / Glue	**Excel**	**openpyxl / xlwings**	Read/write params, logs	Easy handoff for steering group.
	Databases / REST	**sqlite3 , requests**	Persist runs; call cloud APIs	For traceability & cloud tools.

Figure 1: Overview of software used in DfAM/L-PBF and their Python compatibility.

integration can be done through platforms such as ModeFrontier or Python-based frameworks.

Many of these tools can be integrated or automated using Python. For example, FreeCAD has a native Python API, ANSYS provides the PyAnsys library, and Abaqus uses Python as its primary scripting language. CATIA and SolidWorks can be controlled through their COM interfaces, and Excel can be automated using the `openpyxl` or `xlwings` libraries. In practice, this allows a single Python script to manage a complete workflow: adjust CAD parameters, export the geometry for simulation, execute analysis runs, and log results automatically in Excel. This significantly reduces manual file handling, minimizes data loss, and makes it possible to run batch analyses and optimization loops. Figure 3 below provides an overview of the software used in the project domain and their level of Python compatibility.

6. How can Python be used to solve some of the problems of the current process?

Python can remove manual handovers between tools and make the DfAM workflow reproducible. A script can (i) update CAD parameters, (ii) export geometry, (iii) launch simulations, and (iv) collect results in a single run. This reduces file handling and format mistakes, enables batch studies and design-of-experiments, and supports closed-loop optimization where results automatically guide new parameter choices. In practice, Python reads a small configuration (e.g., wall thickness, build angle), modifies the CAD model, calls a solver, extracts key performance indicators (KPIs) such as stress, displacement or support volume, and logs everything to Excel/CSV. The result is a consistent, traceable pipeline that saves time and avoids late-stage redesigns caused by fragmented software use.

7. How does integrating python script with current tools used for DfAM/L-PBF work?

Integration is achieved with simple, well-defined interfaces between stages: **CAD** → **AM prep** (optional) → **Simulation** → **Evaluation/Optimization**. Python connects each stage using one or more of: (a) *API/COM* (e.g., CATIA/SolidWorks/NX, ANSYS/Abaqus) to set parameters and read results directly; (b) *CLI* via `subprocess` to run external programs headlessly; and (c) *file-based* exchange (STEP/STL/CSV) for robust handoffs. A minimal loop is: set named CAD parameters → export STEP/STL → run the solver → parse results → log KPIs → update parameters if constraints are violated. This modular pattern keeps the code flexible: swapping a CAD tool or solver only requires changing a small "connector" rather than the whole workflow.

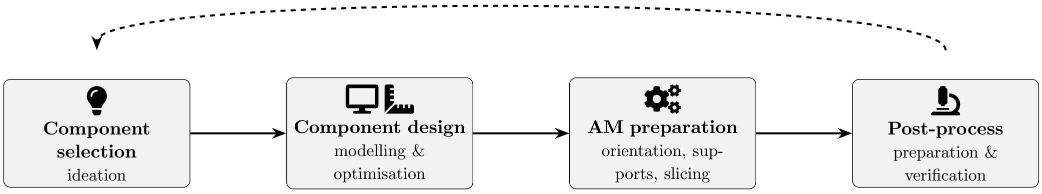


Figure 2: Four steps in a DfAM workflow with a feedback loop from post-process back to component selection.

8. What design methods exist currently and how do they work?

(a) **Topology Optimization:** Topology Optimization (TO) is a design method that helps create strong yet lightweight structures

It functions by determining where material is necessary to withstand stress and where it can be removed.And it started by defining loads, design limits, and other parameters, and the software then gradually removes excess material from low-stress areas while keeping it where it's needed most. The result is an optimized structure that often has an natural look. This technique is widely used to design lightweight components such as aerospace brackets and automotive parts, where reducing weight without sacrificing strength is essential. [8]

(b) **Generative Design:** Generative design is when a computational algorithm or artificial intelligence is used to iteratively generate a large pool of design proposals, based on user-defined constraints [9]. In a way the method can be described as an extension of topology optimization, which helps a designer put material in the right places based on optimizing structural performance within a defined design space. Unlike TO, that only really considers structural strength and weight fractions, generative design can be used to optimize for many different parameters with considerations for manufacturability. When utilizing GD within the product development process it can be used as a great aid in idea generation by inputting different values for all the parameters and "exploring" the design space for inspiration [10]. The method can also be a great tool for idea / design development, where the designer can input values for the parameters that align with the design goals to generate relevant design proposals. [10].

(c) **Lattice Structures:** Lattice structures are patterns of unit cells (e.g., gyroids, octet trusses) that replace solid geometry, leading to a major mass reduction [8]. It can also be used to create components with tailored stiffness and improved heat transfer properties. These structures are commonly used for things like Implants (bone scaffolds) and heat exchangers.

9. What type of components are generally manufactured with L-PBF?

Additive Manufacturing in general makes it possible to manufacture components that were not possible with traditional subtractive manufacturing. Complicated shapes and lattice structures that were previously not possible, makes for better, more flexible and an easier manufacturing process. In general, much of the focus of additive manufacturing is laid on polymers, since its comparatively more expensive and challenging to produce metallic parts. Powder bed fusion is one of the best technologies for making small, low volume, and complex metallic parts.

Based on the literature, a variety of specific components have been simulated for additive manufacturing. The table below summarizes the selected studies and the types of components produced.

Component	**Source**
Brake caliper	[5]
Load bearing formula student part	[11]
Piston rod	[12]
Horse saddletree	[13]
Connecting rod	[13]
Stem	[8]
Turbine blade	[8]
Jet engine bracket	NaN

Table 1: Component creation simulated using additive manufacturing

10. What does a typical testing standardized component look like in AM?

Multiple attempts have been made to produce a standardized component for additive manufacturing to assess the quality and accuracy of the machine itself. These parts all include certain structures that are of relevance, such as circular and arced features, straight, parallel and perpendicular features, holes and bosses, and fine, freeform, and freeform features, all in multiple planes as well as in the centre and close to the edges of the machine. All in all, you want to test all possible features that an additive manufacturing machine could produce. For our purposes, however, we would like to try the software's and the connection between different software's possibilities and faults on a component that can be controlled parametrically. So, while it might be interesting to still incorporate as many as the previous features as possible, the parametric constraint should still be seen as the most important one, and because of that, our proposed feature might be less complex in its geometry [14].

3 Conclusion

The results from the literature study are used to address project related questions that emerged during supervision meetings with the project supervisor, Anton Wiberg.

3.1 Project related questions

- **What is L-PBF?**
  Laser powder bed fusion is an AM method in which a laser is utilized to induced fusion in the powder, this is done layer by layer until the final shape is reached. The method, like most AM processes, is very material efficient and precise, while supporting very complex geometries and enabling integration of components. It is limited in speed, meaning it is not optimal for mass production but is great for mass customization and prototype work.

- **Process challenges**

  The main process challenges discovered in the literature study are maintaining consistency throughout manufacturing. Imperfections during production caused by various reasons lead to no two products being completely identical. This can lead to qualitative errors in the finished product. Other issued voiced by the authors of the examined literature describe density related challenges when producing components using the L-PBF method, stressing the importance of thoroughly planning the build direction with density in mind. Related to this the design of the support structures can be challenging to incorporate, since different structure design allows for different benefits and take-backs. Therefore, educated design choices connected to the support structures need to be made when planning and designing for additive manufacturing.

  As of now, using the technique is not economically feasible for companies to produce what is described as large products using L-PBF, due to production time and physical logistics. Most papers describe the production of what is described as "smaller products", often items such as rods and calipers.

Generally, the process requires a lot of iterative manual labor, jumping between different programs aimed to achieve different goals. This creates a time-consuming environment where changes in one program can cause issues that need resolving in another when exporting geometries or other data. This challenge does not only affect the existing process, but also overlaps with the automation challenges. Below is a compiled list of the identified automation challenges.

- **Automation Challenges**

  Based on our understanding through literature survey we found DfAM process has many Automation challenges, several automation issues have been identified and listed down Below [5, 13, 15]

  - Different softwares involved throughout in DfAM process
  - Model file format will change through passing through all these software Eg(.prt file to step and step to stl)
  - Annotations and tags created to apply loads or boundary condition on surfaces model for next process cannot be recognized by other software
  - Communicating with python scripts with different software might work or may not work.
  - Predicting wait time to run next script in loop might vary on simulation and optimization time and this might vary and create problem to pipelined code if proper delays are not given.
  - Not all activities in process of DfAM can be automated using script because some complicated task is done better by human then the script automation
  - Generalizing the code scripts for variety of components might break code and may not work on all the components or scenarios.

- **How does an overall DfAM process look like?**

  The process can be divided into three quite distinct phases, these being: (i) Initial design definitions where interfaces and loads are defined, (ii) simulation & optimization where the load case is used to generate an "optimal" geometry for the problem. Last is (iii) the "process simulation" and manufacturing phase where a slicing tools is used to covert the model into appropriate layers, as well as simulate the required support structures before final printing. The flow can be observed in the figure below.

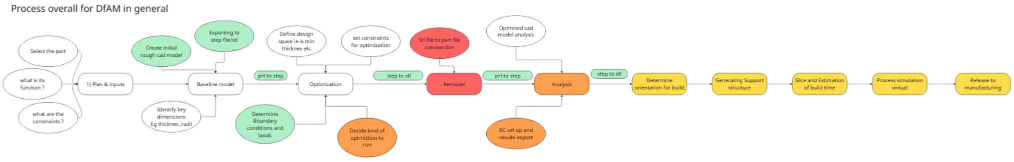


Figure 3: An overview of the DfAM process, green means it can be automated, red means it cannot be automated, orange means it can be semi-automated, and yellow means yet to be explored.

- **What types of simulations are necessary during development?** Depends heavily upon what the specific component requirements are, the only near-constant simulation is the ”process” simulation which simulates where support structures are required and how the part will be built in general. Other common simulations that are performed during the design phase are presented below:
  - Stress deformation analysis
  - Thermal deformation analysis
  - Fatigue analysis
  - Topology optimization
  - Lattice/infill optimization

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