Development and Validation of Energy Simulation for Additive Manufacturing

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Abstract

Additive manufacturing (AM) is a promising manufacturing technology towards cleaner production systems. Nevertheless, recent studies state that environmental benefits of AM are case-specific and need to be evaluated and confirmed in the design phase. To enable the energy performance evaluation in the design phase, developing convenient tools for energy prediction of AM has been an important research task. Aiming at this problem, this paper presents the research for energy modeling, simulation implementation, and experimental validation of an energy simulation tool of two AM processes: Selective laser melting (SLM) and Fused deposition modeling (FDM). The developed simulation tool can be conveniently used for energy consumption quantification and evaluation during the product and process design for AM.

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1 Introduction

Additive manufacturing (AM) is a promising technology to improve sustainable performance of production systems [16]. AM enables the design and manufacturing of novel geometrical features like lattices and hollow bodies which are not possible or only with high expenses to produce with conventional manufacturing technologies [27]. The enhanced design freedom implies better functionalities and more environment-friendly performance of products [15]. Besides, AM requires no tools, dies, or lubricants, and therefore, the absence of peripheral accessories and materials lead to savings of resources that would be used to manufacture, maintain, transport and operate them [32]. In AM, components can be produced close to their final desired shapes, leading to less material waste and energy consumption.

Nevertheless, recent studies state that the environmental benefits of AM should be regarded more critically, especially in terms of energy performance [30]. For example, Kellens et al. state that specific energy consumptions (SEC) of AM processes can be one or two orders of magnitude higher than conventional cutting or casting processes [24], and Gutowski et al. observe that adiabatic efficiency of laser-based AM machines for melting steel powder

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mainly ranges from 9 % to 23 %, and for aluminum powder ranges from 3.6 % to 7 % [14]. The SEC for producing different metal powders ranges from 7.02 MJ/kg to 23.8 MJ/kg depending on materials and processes [24]. Moreover, Baumers et al. and Peng et al. state that the environmental benefits of AM should be evaluated and confirmed in the design phase before AM is implemented [2, 30]. Therefore, energy consumption prediction and evaluation of AM in the design phase have been emerging research topics. Current methods for energy measurements of AM mainly rely on experiments (e.g., [25, 10, 9]), which are not appropriate for the design phase because it is time- and cost-spending, since process time of an AM process can be up to days or weeks depending on the AM systems and process parameters. Aiming at this problem, this paper presents the development and validation of an energy simulation tool of AM, which enables a fast energy prediction for a given product design and AM system in the design phase [39, 40].

2 Background

2.1 Additive manufacturing (AM)

2.1.1 Definition and terms of AM

The standard ISO/ASTM 52900 defines the term "Additive Manufacturing" as " (...) process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies (. . .)" [19]. The German standard VDI 3405 proposes a similar definition that an AM process is regarded as "(..) manufacturing process in which the workpiece is built up in successive layers or units (. . .)" [36]. In addition, different synonyms like 3D printing, layered manufacturing, generative manufacturing, free-form fabrication can be found in literature. The most nominal one is "3D printing", which indicates that AM processes are "(..) 3D analog to ubiquitous 2D printers (. . .)" [5]. In 2009, the ASTM F42 Technical Committee on AM hold a meeting in West Conshohocken, Pennsylvania, in which the term "Additive Manufacturing" was formally selected as the name of processes for joining materials to create parts [5]. Afterwards, the term "Additive Manufacturing" was embraced by ISO Technical Committee TC 261, which is responsible for developing a series of standards for AM processes. Today, the term "Additive Manufacturing" has been adopted internationally by research communities.

2.1.2 Difference between AM and conventional manufacturing (CM)

Generally, a manufacturing process is described as a combination of operations for the production of geometrically defined solid bodies (German: " (..) Verfahren zur Herstellung von geometrisch bestimmten festen Körppern (. . .)") [8]. Considering the shaping mechanisms of materials, manufacturing processes can be distinguished between the following three types, as depicted in Figure 1 [19]:

- **Formative shaping**, in which the desired geometry is created by applying pressure to a body of raw material, e.g., casting and bending;
- **Subtractive shaping**, in which the desired geometry is created by selective removal of materials, e.g., drilling, turing, and milling;
- **Additive shaping**, in which the desired geometry is made by successive addition of material

The main difference between them is the volume change of a workpiece [11]. In formative shaping, by assuming a constant material density, the volume of a workpiece before and after the shaping is constant, see V_1 and V_0 depicted in Figure 1. In subtractive manufacturing,

V_1 is smaller than V_0 because of the material removal, while only in additive shaping, V_1 is larger than V_0 because the material is applied layer by layer. Therefore, the changing mechanism of volume during the material shaping is a fundamental criterion to distinguish AM processes from other manufacturing processes.

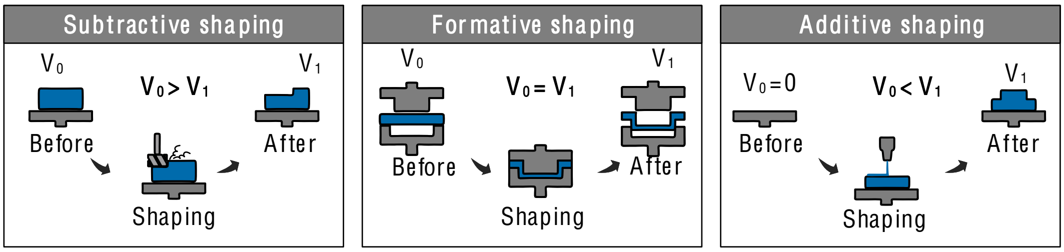


Figure 1 Distinguish between AM and conventional manufacturing (according to [11]).

2.1.3 AM process categories

The standard ISO 17296 has proposed seven major AM process categories [18]. Each category is characterized by its own processable feedstocks, system characteristics, and suitable application areas, as described in the following and depicted in Figure 2 [38, 18, 31]:

- **Vat photopolymerization** uses a light source (e.g., UV radiation) to harden photo-curable liquid or ceramic paste with mixed photo-curable materials, and it is the first commercialized AM process. Vat photopolymerization can be used to produce prototypes, patterns, or presentation models due to its high accuracy and fine surface finishing.
- **Material jetting** uses a spray nozzle to deposit droplets of build materials on a platform. The most common feedstock is liquid or semi-liquid made by single material or composites. By defining the composition of different materials, material jetting process is capable of processing components with unique electrical, optical or other physical properties [38, 13].
- **Binder jetting** dispenses bonding agent to a selective area of a powder bed and can be used to produce plastics, metals, or ceramics, as long as the material is in powder form. By using multiple nozzles, material jetting can achieve a higher build rate and can be used to produce prototypes or functional parts. For printed metal or ceramic parts, a post-sintering process is required to fully densify the part.
- **Material extrusion** squeezes filamentary materials or paste (e.g. plastics or structural ceramics) on a platform to create a part. Due to its convenient usability and low-priced machines and materials, material extrusion has been widely adopted for rapid prototyping. Today, material extrusion can be used to produce metal parts if metal particles are filled with a binder matrix into filaments.
- **Powder bed fusion** uses thermal energy like laser beam or electron beam to fuse powders in selective region of a powder bed. Today, powder bed fusion is one of the most important process categories for producing metal parts delivering complex functionalities, i.e., tools or end use parts.
- **Directed energy deposition** uses focused thermal energy to create a local molten pool, in which the material powder or wire is continuously feed and melted. Directed energy deposition is another promising process category for producing metal parts and can be integrated into conventional milling machine tools to enable a hybride additive-subtractive manufacturing.

- **Sheet lamination** bonds sheets of material to form an object. The range of the processable materials is very wide, as sheets can be metal, plastic, ceramic, paper, wood or composite. Sheet lamination is suitable for producing models, patterns, or prototypes that have less requirement on geometrical complexity and accuracy.

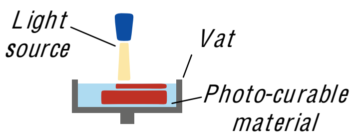
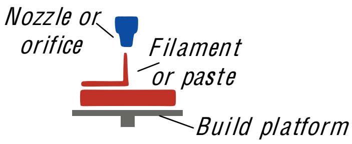
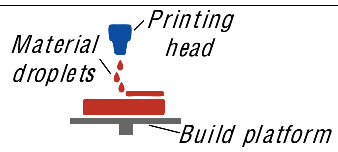
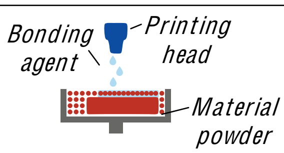
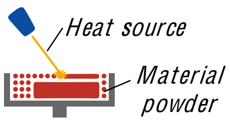
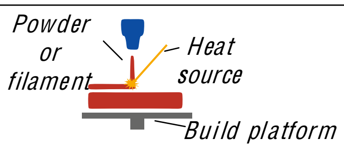
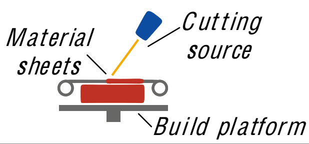
Process category	Schema	Material	Application
Vat photopolymerization	 Light source; Vat; Photo-curable material	• Polymer • Ceramic	• Prototyping • Functional testing • Tooling patterns • Detailed parts • Presentation model
Material extrusion	 Nozzle or orifice; Filament or paste; Build platform	• Polymer • Metal • Ceramic • Composite	• Prototyping • Functional testing • Tooling patterns • Personal use
Material jetting	 Material droplets; Printing head; Build platform	• Polymer • Metal • Ceramic • Composite	• Concept model • Limited functional testing • Colored design models
Binder jetting	 Bonding agent; Printing head; Material powder	• Polymer • Metal • Ceramic	• Prototyping • End use parts • Casting/forming tools
Powder bed fusion	 Heat source; Material powder	• Polymer • Metal • Ceramic	• End use parts • Functional testing • Rapid tooling • High-temperature applications
Directed energy deposition	 Powder or filament; Heat source; Build platform	• Metal	• End use parts • Functional testing • Rapid repair/overhaul • High-temperature applications
Sheet lamination	 Material sheets; Cutting source; Build platform	• Polymer • Metal • Ceramic • Composite • Paper	• Form testing • Tooling patterns • Less detailed parts

Figure 2 Classification of AM processes (own illustration according to [18]).

2.2 Energy performance of AM

2.2.1 Debates on the energy performance of AM

Energy is a physical property that can be transferred between objects and expressed by different forms, while energy performance describes the energy consumption, energy efficiency, and energy usage of a system or process [17]. In the current research, there are two different views on the energy performance of AM. One group of researchers believes that AM has the potential to reduce energy consumption in manufacturing industries, while the other group believes that AM's potential may be very limited and difficult to realize. On the positive side, the following perspectives are observed:

- **Lightweighting of products**: AM enables the lightweighting using topology optimization, lattice structures, hole body, lightweighting materials etc. On the one hand, lightweighting leads to less material usage for manufacturing a product, and on the other hand, lightweighted products can be beneficial for the use phase. For example, aircraft with less weight requires less fuel consumption [16].
- **Less material waste**: For powder-based AM processes like selective laser melting (SLM), the powders that are not used in a build task can be recycled, screened, and reused [32]. The scraps with AM are less than conventional manufacturing, and they can only be found in limited places, e.g., support structure.
- **Absence of product-specific tools or peripheral substances**: AM requires no dies, cutting tools, fluids, or other auxiliary substances or devices. Therefore, their production, transportation, storage, operation, maintenance, and disposal are not required, which indicates that energy usages related to these steps are saved [27].
- **Shortening of supply chains**: AM enables assembly integration in which multiple parts are integrated to single complex parts. Therefore, the relevant manufacturing steps and secondary processes (e.g., storage and transport) are reduced, leading to a shorter and more flexible supply chain. By 2025, primary energy and CO_2-emission intensities of industrial manufacturing supply chains can be reduced by up to 5% through AM [12].
- **Rapid repair and remanufacturing**: At the use phase, products can be repaired by AM, and hence, the lifecycles of products are extended. At the end-of-life phase, products can be remanufactured and reused. Finally, Extension of the lifecycle of an existing product enables the saving of energy and materials that would be used for producing a new one [26]

In addition to these positive views, the following concerns about potentials of AM to improve the energy performance still exist:

- **Production of feedstock**: Different AM processes require different shapes of feedstock, while conventional manufacturing is not very sensitive to the shape of feedstock [24]. For metal powder-based AM processes like binder jetting and powder bed fusion, metal powers should be produced by water or gas atomization that requires a significant amount of energy [6].
- **Need of post-processing**: While cutting tools or fluid are not needed during the in-process of AM, they are still used during the post subtractive processing, in order to improve the surface quality and geometrical accuracy of AM parts [35]. Thus, the tools and auxiliary substances that are claimed to be absent with AM are still not avoidable. Consequently, the energy usage that should be saved due to their absence is still there.
- **Lower efficiency and high SEC** In metal AM processes, the heat exchange between heat source and metals cause high energy waste due to radiation, reflection, conduction, and convection. The adiabatic efficiency of laser AM process (ratio between actual build rate with heat loss and theoretical maximal build rate without heat loss) ranges from 3.6% to 7% for aluminum powders, and from 9% to 23% for steel powders [14]. Moreover, SEC values of AM processes can be 1 to 2 orders of magnitude higher than conventional machining and molding processes [24].
- **Long process time** Build time of different AM processes ranges from hours to days depending on machines and process parameter sets[1]. Longer process time implies more electricity consumption and a higher risk of failure. Once an error occurs during the process, the build task needs to be repeated, leading to more material and energy expenses.

2.2.2 Current research questions related to energy issues of AM

In accordance with the debates on the energy performance of AM, the following research questions are essential at the current research background:

- **Quantitative energy performance assessment of AM processes**: The energy performance of AM can be influenced by different factors such as part size, build orientation, batch size, process parameters, machine configuration, etc [24, 2]. Thus, the quantification and evaluation of different AM processes and systems with varying influence factors are important research tasks.
- **Comparison of AM with conventional manufacturing in multiple life stages**: In different life phases, AM may have advantages or even disadvantages compared to conventional manufacturing, e.g., production, usage, service, disposal [2]. Therefore, energy performance of AM versus conventional manufacturing should be compared throughout the lifecycle to avoid creating a simplistic picture [2].
- **Raw materials and feedstock**: Current literature has only limited studies addressing technical and environmental issues of production of feedstock for AM, e.g., [9, 29]. The energy consumption and primary resource usage for material extraction and feedstock production of AM should be quantified and evaluated.
- **Eco-design**: Since energy performance of AM may be a critical problem, how to improve the energy performance of AM has been another important research task [2]. A promising approach is eco-design in which environmental aspects are considered in design phase, and future works should pay more attention on this issue [2, 30].

2.2.3 Research questions for this research

In accordance with the current research background, this research specifically aims at the development and validation of an energy simulation for AM. Choosing this research question encompasses the following three motivations:

- **Systematical exploration and understanding of the energy consuming behavior of AM**: AM systems consume electricity and transfer it into movement of platforms and heat to melt materials. Thus, AM processes involve different forms of energy, and a holistic description and understanding of them is the prerequisite to optimize the energy performance of AM.
- **Convenient and accurate energy prediction in the design phase**: As mentioned before, eco-design for AM requires the quantification and evaluation of energy performance of AM in the design phase. However, current methods to quantify energy consumption of AM systems are experiments that are time- and cost-spending. Therefore, proposing a reliable simulation tool will significantly contribute to supporting eco-design for AM.
- **Lack of predictive models of energy consumption for AM**: In the current literature, only very few studies mentioned the development of energy predictive models for AM, e.g., Baumers et al. proposed empirical methods (black box approach) for energy prediction of SLM process [3]. Our research adopts a physical method (white box approach) in which the energy flow of AM is modeled by physical variables, leading to a methodological contribution to current literature.

3 Methodology

3.1 Reference AM processes and machines

In this research, two AM systems are selected as the referential research objects. The first one is Concept Laser Mlab, which is categorized in SLM process [7]. Concept Laser Mlab is equipped with a laser device for producing metal parts, and the feedstock includes different metal powders such as aluminium, steel, and titanium alloy. The maximal size of a build platform is 90×90 mm^2, and scan speed of the laser beam can be up to 7 m/s. During a build process, inert gas is required to avoid oxydation. For different materials, different inert gas is needed, e.g., argon for aluminium, and nitrogen for steel. The second AM system is Ultimaker 3 that belongs to FDM process and is capable of processing thermal plastics such as PLA, ABS, PVA, and TPU [33]. Ultimaker 3 is equipped with two extruders that melt and extrude build material and support material, respectively. After the part is printed, the support structure needs to be revomed. Figure 3 shows photos of the two AM systems including their auxiliary devices and examples of manufactured parts.

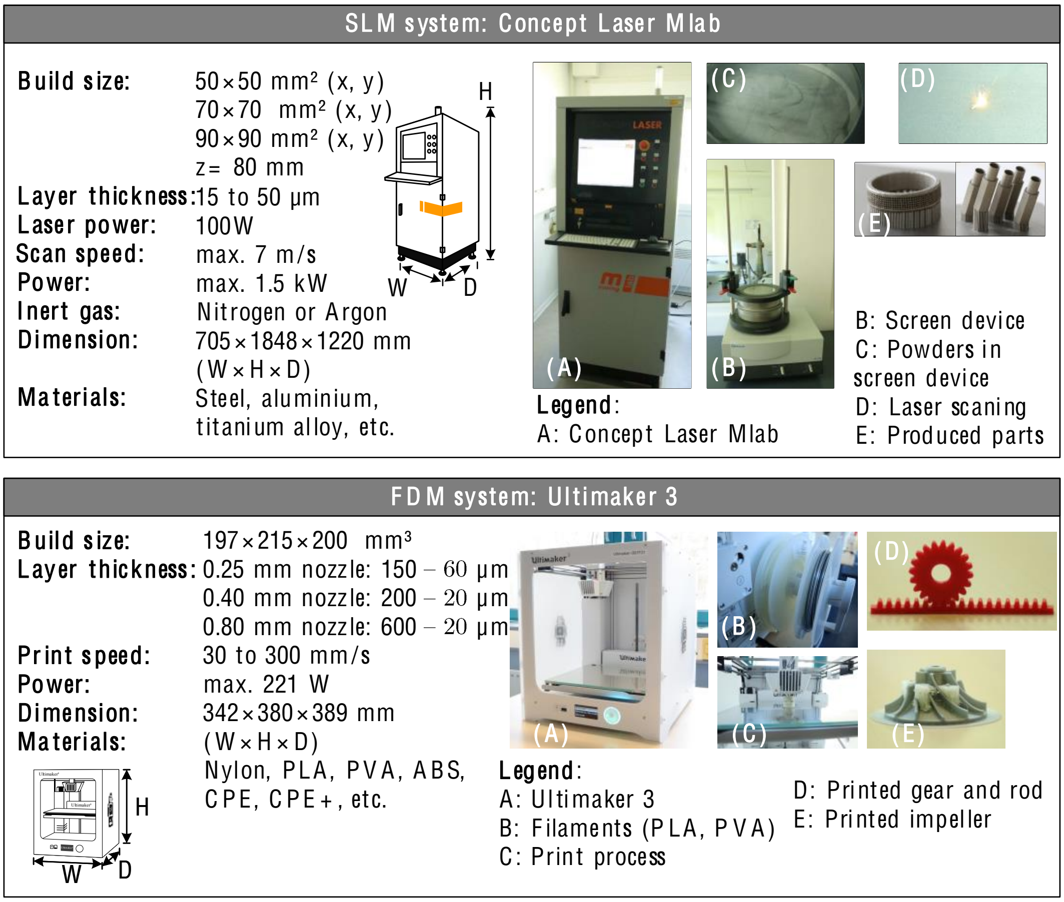


Figure 3 Reference AM systems for this research.

3.2 System boundary and approach

3.2.1 Definition of system boundary

Manufacturing can be discussed between different levels, as depicted in Figure 4 [37]. In this research, the research focus is limited to the workstation/machine level, neglecting other issues like production feedstock or post-processing. According to standard ISO 14955-1, the system boundary for energy evaluation of a machine tool should include the machine tool itself and its auxiliary devices [20]. Thus, this research adopts this standard and considers an AM system as a system containing at least one AM machine and its peripherals such like screen device and vacuum cleaner.

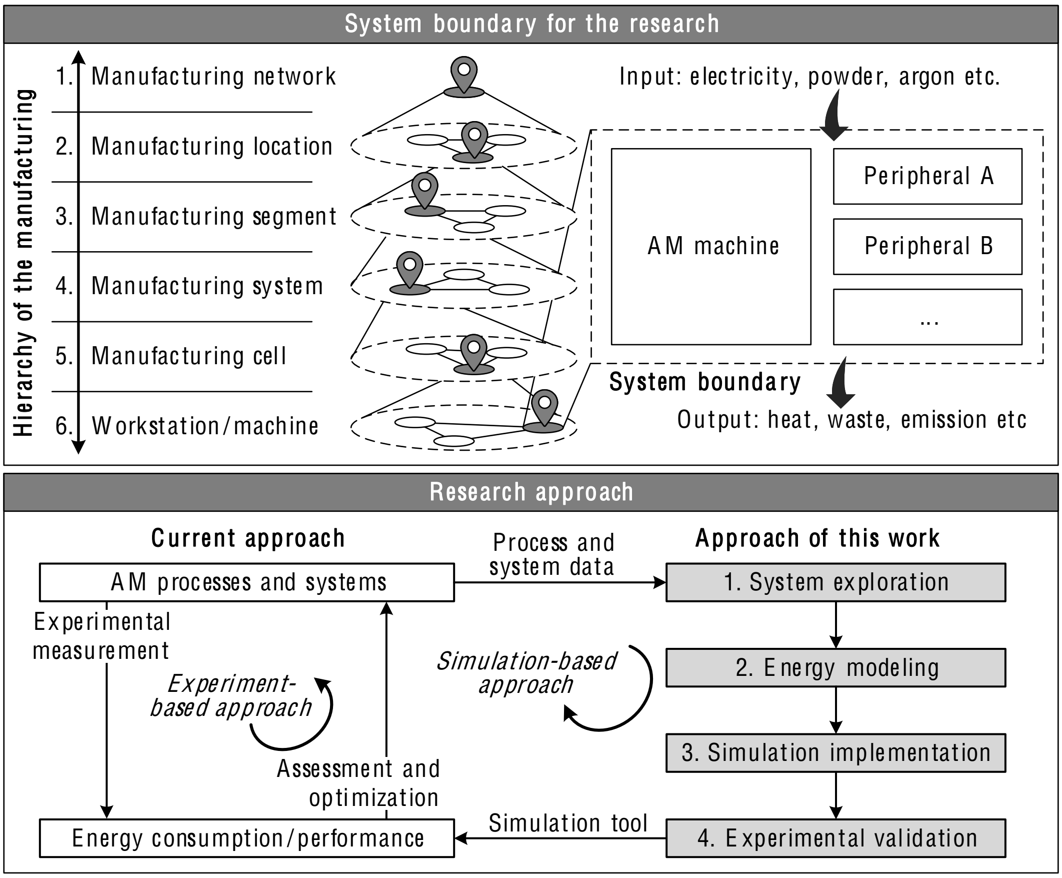


Figure 4 Research approach and system boundary.

3.2.2 Research approach

Compared to conventional experiment-based approach for measuring and analyzing the energy consumption of AM, our research approach for the energy simulation development and validation encompasses the following four phases, as illustrated in Figure 4:

- **System exploration**: In this phase, the structure of the AM-machine and the functions of system components related to power consumption or exchange are analyzed. Furthermore, the system components that should be considered in the energy modeling are defined, and their information are collected from internal or external data sources, e.g., data sheets and circuit diagrams.

- **Energy modeling** In the second phase, the energy flows between system components are modeled using bond graph because bond graph enables the modeling of power flows between multiple physical domains based on a unified terminology. [23]. First, the related energy domains of the energy flow are analyzed and the power variables and multiports are defined. Afterwards, the bond graph of the AM system is created. For more information about bond graph methodology refer to [23, 4].
- **Simulation implementation**: In the third phase, based on the bond graph, a simulation tool is developed based on the MATLAB® platform. First, based on the bond graph, the equivalent simulation models of system components are created using Simulink. Afterwards, by running the Simulink models, a power database is generated. By programming a GUI using the function module *AppDesigner* of MATLAB®, an energy simulation tool is developed. The simulation approach developed in this paper is called Numerical Control (NC) code (also called G-code) and database-driven approach, which is explained in the appendix.
- **Experimental validation**: In the last step, experiments are carried out to verify the simulation accuracy of the simulation tool. The power meter is YOKOGAWA WT 1806 [41], and wiring of the measurement adopts standard ISO 14955-2 [21]. For capturing the power data, the sampling time is set as 1 s.

4 Result and discussion

4.1 Energy simulation tool

4.1.1 Data structure and simulation logic

The data structure of the simulation is illustrated in a functional flow block diagram, as depicted in Figure 5.

The first function is the import of .stl-file and .lsr-file (or .gcode-file), from which the facet data of a part and the layer data of a process are extracted, respectively. Afterwards, while the facet data are used to visualize the geometry, the layer data are used to facilitate the energy simulation. After the simulation, the power curves of the AM machine and peripherals are visualized , and the simulation result including power curves and data tables can be exported.

The core function of the simulation tool is *energy simulation* containing eight subfunctions, as shown in Figure 5. Followed by the third function *extract layer data*, time parameters are converted to the time array with a sampling time of 1 s. To mention is that the sampling time cannot be too short. For conventional manufacturing like milling or drilling, the sampling time for obtaining power values can be set to 0.1 s because the process lasts only minutes or tens of minutes [22]. However, for AM processes, the build time can be up to hours or days, and shorter sampling time implies more frequent sampling, leading to a massive volume of data. To avoid this, the sampling time to obtain power values is defined as 1 s. After generating the time array, power values for each system component and point in time are generated from on the database. Finally, after the trapezoidal integration of power and time arrays, the energy values are calculated.

In addition to the NC code-driven approach, this research adopts the use of a power database. In a previous idea, Simulink models are directly integrated to GUI in which the power data of system components are simulated after the time parameters are read. However, the simulation of all these Simulink models is extremely time-spending. Adding a power database, in which the power data of Simulink models are already stored, can significantly reduce the simulation time. The sacrifice for this decision is a reduced flexibility for AM

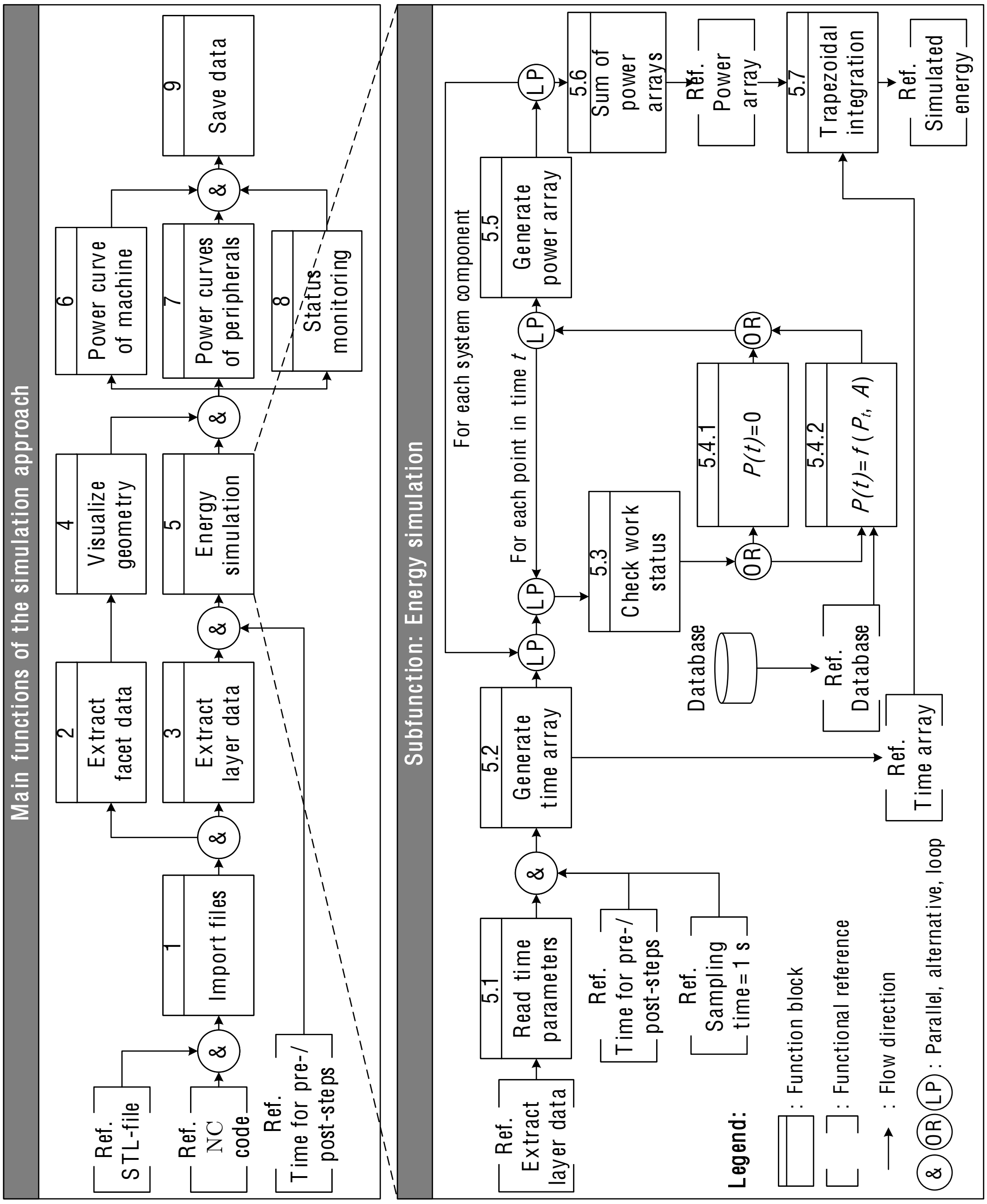
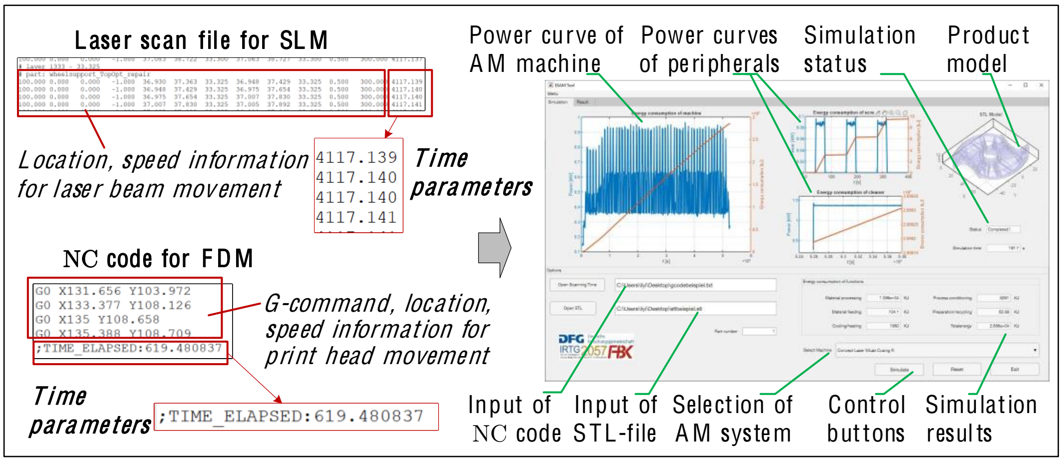


Figure 5 Functional logic of the simulation tool.

system modification (e.g., add a second laser device or change the platform motor). If Simulink models are directly connected with GUI, users need to carry out two steps for system modification: first, change Simulink models, and second, run the energy simulation in GUI. However, if the GUI is connected with a power database, users have to carry out three steps: first, modify the Simulink models, and second, run the Simulink models and update the power database, and third, run the energy simulation in GUI. Nevertheless, if user do not change the AM system configuration, but only change process parameters or product design, the power database-driven simulation can reduce the simulation time from hours to seconds.

4.1.2 Graphical user interface (GUI)

The GUI of the developed simulation software is depicted in Figure 6. The simulation approach is called NC code-driven approach, in which NC code of a process design should be generated at first and then imported to the GUI to start a simulation. Figure 6 shows examples of the NC codes, in which movement command, location information, and time parameters are contained. In this research, *.lsr* and *.gcode* file formats are used for the simulation of Concept Laser Mlab and Ultimaker 3, respectively, and they can be exported by the software Netfabb and Ultimaker Cura, respectively [28, 34].



■ **Figure 6** GUI of the simulation software.

4.2 Analysis of the simulation accuracy

4.2.1 Accuracies for SLM

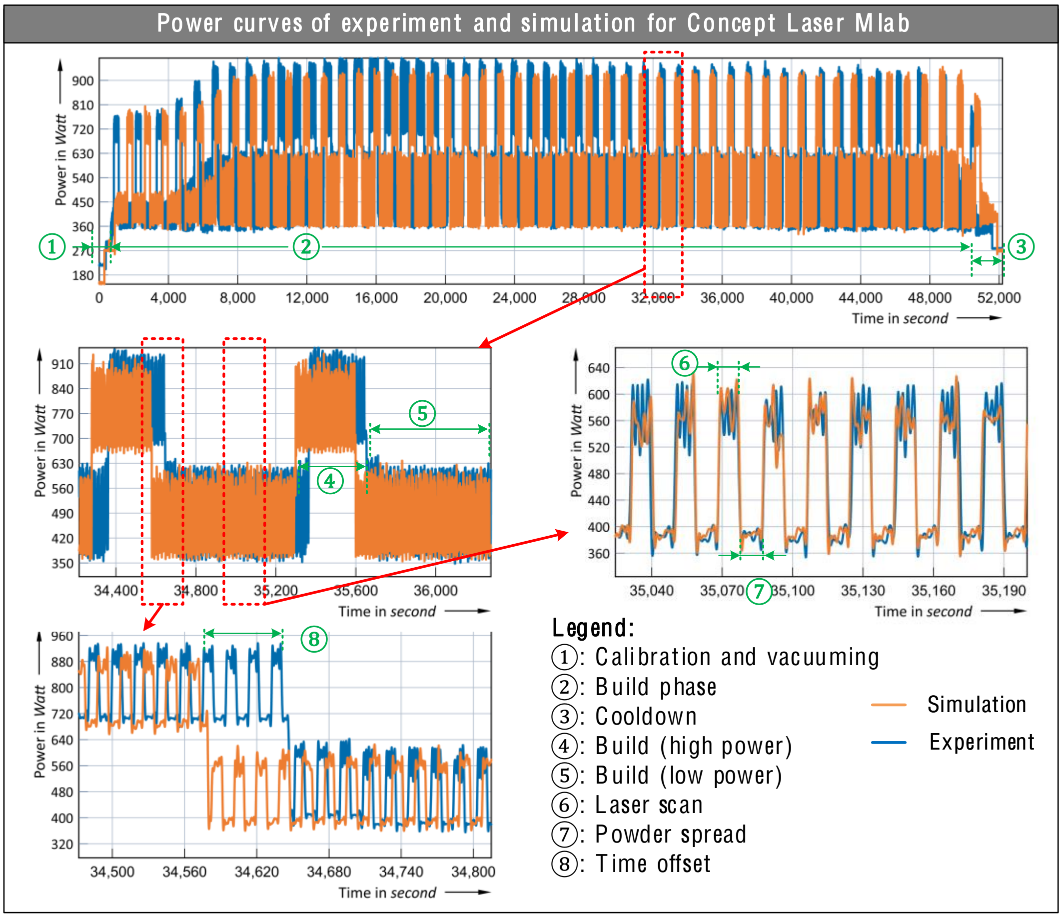
The power curves of the simulation and experiments for Concept Laser Mlab are depicted in Figure 7 in which the power curve can be characterized by three stages. While the first stage indicates the calibration and vacuuming of the build chamber ((1)), the second and third stages describe the build of part ((2)) and the cooldown ((3)), respectively. The second stage can be further divided into two build modes, as indicated by ((4)) and ((5)) in Figure 7. The cyclic operation of the compressor in cooling device leads to a cyclical power increase by approximately 300 W. By zooming the power curve, another periodical power increase is observed, as indicated by ((6)) and ((7)), implying the laser scanning and powder spreading, respectively. The laser scanning leads to a power increase by approximately 210 W.

Although the simulated power curve and the actual power curve generally fit, there are still deviations. One of them is the time offset, as marked by ((8)). The reason is that time parameters in NC code files used for simulations vary from the actual time parameters. Thus, the timelines of simulations and experiments are not perfectly matching up.

The table in Figure 7 summarizes the result of simulations and experiments, including the calculated evaluation indicators. The simulation accuracy ACC_E is defined by the following equation, in which E_{sim} and E_{ext} represent the energy consumption of simulation and experiment respectively:

$$ACC_E = \frac{\Delta E}{E_{exp}} = \frac{|E_{sim} - E_{exp}|}{E_{exp}} \tag{1}$$

In four experiments, mean ACC_E is 96.43%. Since it is higher than 95%, it can be concluded that the simulation accuracy is verified and the simulation tool can be used for energy performance quantification and evaluation of Concept Laser Malb.



No.	n_{layer}	t_{build} (min)	E_{exp} (kWh)	E_{sim} (kWh)	ΔE (kWh)	ACC_E (%)
1	2546	874.48	8.03	7.91	0.12	98.51
2	433	181.15	1.41	1.48	0.07	95.04
3	605	153.00	1.10	1.14	0.04	96.36
4	1113	403.40	2.39	2.29	0.10	95.82

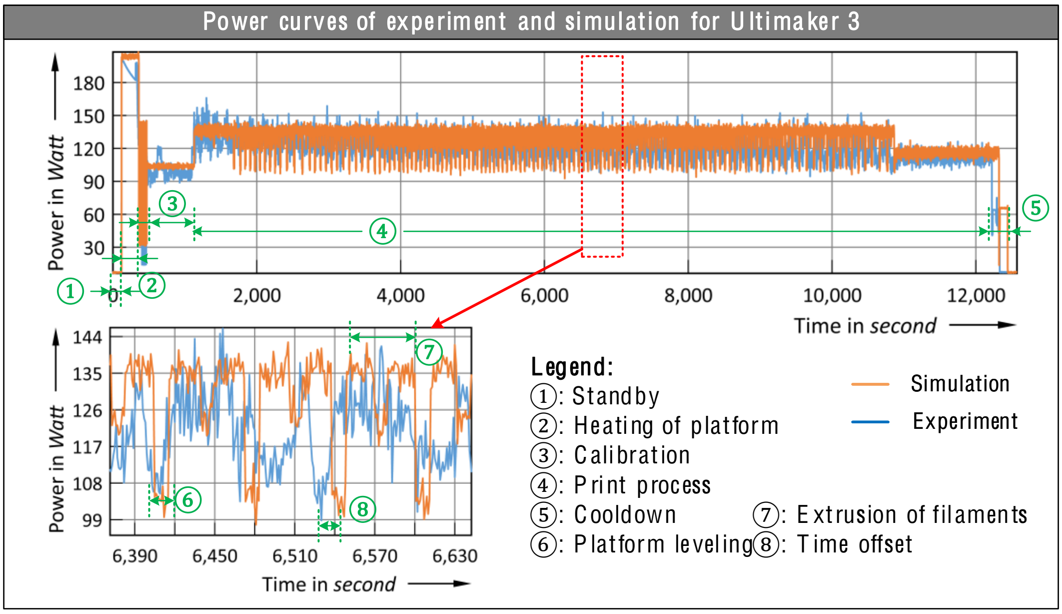
Figure 7 Power curves and experimental and simulated result for Concept Laser Mlab.

4.2.2 Accuracy for FDM

In Figure 8, the simulated and experimental power curves of Ultimaker 3 are depicted, in which five stages are characterized. In the first stage standby, as indicated by ①, the power consumption is approximately 5 W, while during the second stage (②), the platform is heated to 60 °C, and the power consumption is increased to approximately 210 W. Afterwards, in the third and fourth stages, indicated by ③ and ④ respectively, the calibration of the print head and the print process are executed. The power consumption of print process is approximately 130 W. Finally, in the last stage cooldown (⑤), the power consumption falls back to 5 W.

The print process depicts a cyclical behavior, which is caused by the leveling of platform and extrusion of filaments, indicated by ⑥ and ⑦ respectively. Moreover, the time offset is also observed, in which the timeline from the NC code file varies from the real timeline, as seen as ⑧ in Figure 8.

In the experimental verification, eight experiments are performed, with the mean ACC_E of 94.7 %. Main reason for this deviation is the time offset that can be easily impacted by environmental factors. For example, if Ultimaker 3 is turned on in a morning with lower room temperature, it requires more time to heat up and causes higher deviation in time parameters. The solution to eliminate or to reduce these unpredictable influence can be the standardization of the application scenario and workflow for operating Ultimaker 3.



No.	t_{build} (min)	E_{exp} (kWh)	E_{sim} (kWh)	ΔE (kWh)	ACC_E (%)
1	203.18	0.41	0.42	0.01	97.6
2	207.53	0.41	0.43	0.02	95.1
3	264.57	0.52	0.54	0.02	96.2
4	268.60	0.55	0.56	0.01	98.4
5	81.35	0.16	0.15	0.01	94.9
6	83.10	0.16	0.15	0.01	93.3
7	105.12	0.21	0.19	0.02	90.5
8	105.47	0.21	0.19	0.02	91.4

Figure 8 Power curves and experimental and simulated result for Ultimaker 3.

5 Conclusion and outlook

This paper introduces the development and validation of a simulation tool for energy consumption prediction of two representative AM systems. Based on the result of research, the following conclusions can be made:

- Bond graph is a suitable tool for describing the power exchange between system components of AM systems.

- NC code-driven simulation approach enables a high simulation accuracy. In experimental validation, the mean accuracy for both AM systems are approximately 95 %, and the highest accuracy can be up to approximately 98 %.
- Use of power database can significantly reduce the simulation time.
- Time offset is the main reason for causing simulation deviation.

Based on this research, future works should focus on the adaption of this method to other AM processes and systems, as well as implementation of the simulation tool into eco-design for AM methods.

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A Appendix: NC code and database-driven simulation approach

By considering the AM machine as an entire system, its total energy consumption ($\mathrm{E_{AM}}$) is the sum of the energy consumptions of the system components ($\mathrm{E_{Component}}$) within the system; therefore, $\mathrm{E_{AM}}$ can be defined by the following equation:

$$E_{\mathrm{AM}} = \sum_{i=1}^{n} E_{\mathrm{Component\ i}} \tag{2}$$

For every system component, its energy consumption is the time integration of power ($\mathrm{P_{Component}}$). Based on the trapezoidal rule, $\mathrm{E_{Component}}$ in a given time ($\mathrm{T_N}$) can be expressed as follows:

$$E_{\mathrm{Component}} = \int_0^{T_{\mathrm{N}}} P_{\mathrm{Component}} dt \approx \sum_{k=1}^{N} \frac{P_{\mathrm{k\text{-}1}} + P_{\mathrm{k}}}{2} (t_{\mathrm{k}} - t_{\mathrm{k\text{-}1}}) \tag{3}$$

Thus, based on the equations described above, the most important variables for enabling the energy simulation of AM are power data and time data. In the NC code and database-driven approach, the time data of a build task are collected from its NC code, and the power data are acquired from a power database, where the power data of system components are already stored. The functional logic of the NC code and database-driven approach is illustrated in Figure 9 and described below.

In the first step, the time parameters are read from the NC code, based on which a new time array is created in the second step. According to the information of the NC code, the times for different operations can be identified. For example, in Figure 9, it is assumed that the time array is made with a sampling time of 1 s and that during the 10 s for layer 1, 5 s

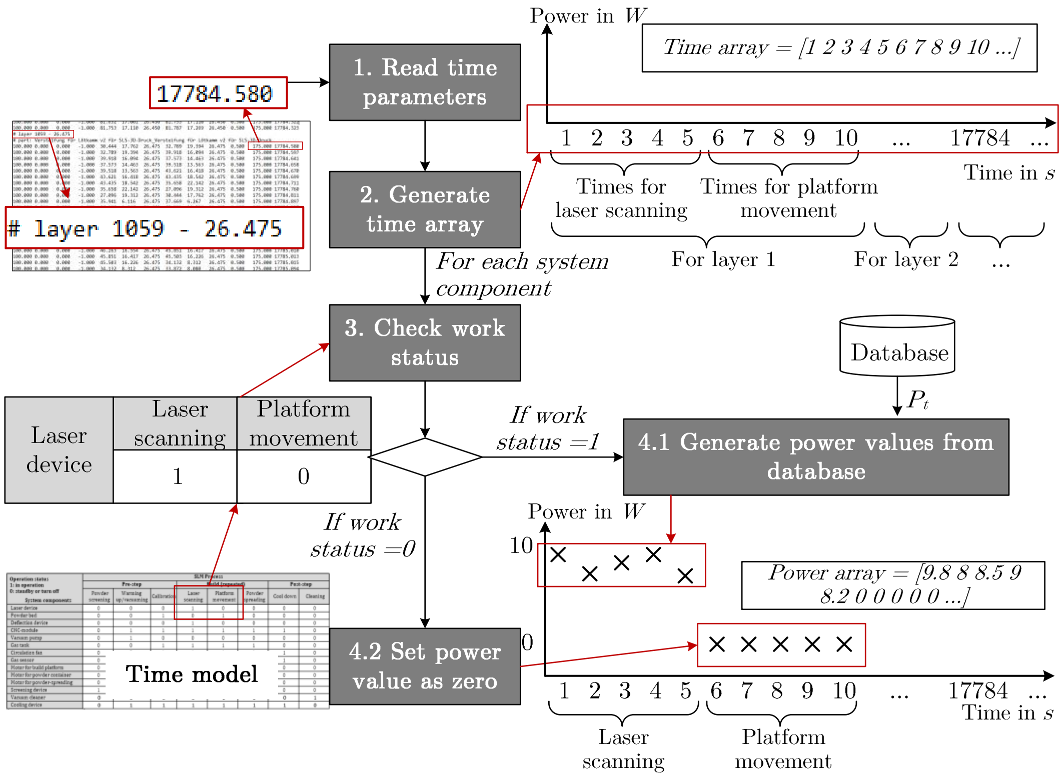

Figure 9 NC code and database-driven approach.

are used for the laser scanning, while the remaining 5 s are used for the platform movement. In the third step, it is to check the operation status of each system component. For example, Figure 9 shows the operation status of the laser device that it is in operation (denoted as “1”) in the laser scanning and standby in the platform movement (denoted as “0”). In the fourth step, when the work status of a system system is “1” during an operation, the power data of this system component should be allocated to the times for this operation, while, when the work status is “0”, the power data of this system component during the corresponding operation are set to zeros. For example, in Figure 9, it is known that the laser device is in operation for the laser scanning and standby for the platform movement; hence, for the laser scanning, the power values of the laser device are generated from the database (note that the values of 9.8, 8, 8.5 etc. are pseudo and do not represent the real power data), while during the platform movement the power values are zeros. By summarizing the power values, a power array for a system component with a same length as the time array can be created. Finally, by adopting Equation 3, the energy consumption of this system component can be calculated, in which the power and time array generated respectively by the database and NC code serve as $P_{Component}$ and T_N. Moreover, by adopting Equation 2, the total energy consumption of an AM system can be determined.