Lehrstuhl für Fertigungstechnik und Betriebsorganisation

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Herausgeber: Prof. Dr.-Ing. Jan C. Aurich

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# Eco-Design for Additive Manufacturing Using Energy Performance Quantification and Assessment

Vom Fachbereich Maschinenbau und Verfahrenstechnik
der Technischen Universität Kaiserslautern
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Doktor-Ingenieur (Dr.-Ing.)
genehmigte Dissertation

von

**Master of Science**
**Li Yi**

aus

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Kaiserslautern, 2021

D 386

To my beloved mom.

送给妈妈

# Vorwort des Verfassers

*"Des Himmels Bewegung ist kraftvoll, so macht der Edle sich stark und unermüdlich.*

*Der Zustand der Erde ist empfangende Hingebung, so trägt der Edle weiträumigen Wesens die Außenwelt"*

*/I Ging/*

Die vorliegende Dissertation entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Lehrstuhl für Fertigungstechnik und Betriebsorganisation der Technischen Universität Kaiserslautern (FBK).

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Zum größten Dank bin ich jedoch meinen Familien verpflichtet. Ihre Unterstützung und ihr Rückhalt haben wesentlich zum Gelingen dieser Arbeit beigetragen!

Kaiserslautern, im Juni 2021 Li Yi

# 前言

*"天行健，君子以自强不息；地势坤，君子以厚德载物"*

*/易经/*

本论文撰写于我在凯撒斯劳滕工业大学制造工程和生产组织研究所担任研究员期间。

首先，我要感谢导师（亦是本所的所长）杨·克里斯蒂安·奥利奇（博士）教授，感谢他在我担任研究员期间对我的信任和指导。我还要感谢来自美国加州大学戴维斯分校先进公路维修及建造技术研究所的所长巴拉姆·拉瓦尼（博士）教授，感谢他担任本论文的外审评委。此外，我还要感谢来自本校工程力学研究所的所长拉尔夫·穆勒（博士）教授，感谢他担任我的博士评审委员会主席。

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最后，我要感谢我的家人，他们的支持为这项工作的成功做出了巨大贡献。

易黎

二零二一年 辛丑 午月 于 凯撒斯劳滕

# Contents

# Abstract

Recent studies on the environmental performance of additive manufacturing (AM) have shown that AM exhibits both complex potentials and challenges at different life stages compared to conventional manufacturing. To assess and ensure the environmental benefits of AM during the design phase, an eco-design approach is required. Existing eco-design for AM approaches described in the literature mainly focus on the use of lifecycle assessment (LCA) to analyze the environmental impacts of AM-specific design solutions. However, since LCA requires a full-process chain model and detailed inventory data, it can only be performed after the design process or in a subsequent design stage. To integrate evaluation activities into the middle stage of the design process, energy performance assessment can be used as an alternative evaluation tool in eco-design for AM. However, the literature still lacks an eco-design for AM method based on energy performance quantification and assessment. By addressing this research problem, this dissertation contributes to the development of a holistic framework to implement eco-design for AM using energy performance assessment. This framework consists of the following three parts: a simulation tool for energy prediction in the design phase; an energy performance assessment model for AM; and a method for carrying out activities in eco-design for AM. To demonstrate the feasibility of the proposed method, three use cases are performed. Based on these use cases, it is concluded that with the use of the proposed method, AM designers will be able to select and develop optimal design solutions based on the energy performance of AM in the middle design stage.

# Kurzfassung

Aktuelle Studien für die Bewertung der Nachhaltigkeit der additiven Fertigung (AF) haben gezeigt, dass AF im Vergleich zur konventionellen Fertigung sowohl Potenziale als auch Herausforderungen in verschiedenen Lebenszyklusphasen aufweist. Um die Umweltvorteile der AF während der Gestaltungsphase bewerten und sicherzustellen zu können, ist der Ansatz des Ökodesigns erforderlich. Bestehende Ansätze zum Ökodesign für die AF fokussieren sich hauptsächlich auf die Verwendung von Ökobilanzen, um die Umweltauswirkungen von AF-spezifischen Gestaltungslösungen zu analysieren. Da Ökobilanzen jedoch ein vollständiges Prozesskettenmodell und detaillierte Inventardaten erfordern, können sie erst in einer späteren Phase oder nach dem Gestaltungsprozess durchgeführt werden. Um die Bewertung in der mittleren Phase des Gestaltungsprozesses zu ermöglichen, kann die Bewertung der energiebezogenen Leistung als alternatives Bewertungswerkzeug im Zuge des Ökodesigns für AF verwendet werden. In bestehenden Ansätzen gibt es jedoch noch keine Methode zum Ökodesign für AF, die auf der Quantifizierung und Bewertung der energiebezogenen Leistung basiert. Daher zielt die vorliegende Dissertation auf die Entwicklung und Validierung eines Konzepts zum Ökodesign für AF mittels der Quantifizierung und Bewertung der energiebezogenen Leistung der AF ab. Das Konzept umfasst drei Bestandteile: ein Simulationstool zur Quantifizierung des Energieaufwands der AF in der Gestaltungphase; ein Modell zur Beschreibung und Bewertung der energiebezogenen Leistung der AF; und eine Vorgehensweise zur Durchführung des Ökodesigns für AF mittels des entwickelten Simulationstools und Bewertungsmodells. Um die Machbarkeit des Konzepts zur validieren, werden drei Anwendungsfälle durchgeführt. Die Ergebnisse haben gezeigt, dass das entwickelte Konzept ein effizientes Instrument ist, um die Umweltvorteile der AF in der Gestaltungsphase zu ermitteln und zu gewährleisten.

# Deutsche Zusammenfassung

Die additive Fertigung (AF) ist ein Oberbegriff für Fertigungsverfahren, bei denen Bauteile durch schicht- oder elementweisen Materialauftrag generiert werden. Durch ihr Wirkprinzip bietet die AF vielfältige Vorteile gegenüber konventionellen Fertigungsverfahren und wird in vielen Branchen angewendet, wie z. B. in der Automobilindustrie oder in der Luft- und Raumfahrttechnik. Diese Vorteile sind beispielsweise die erhöhte Designfreiheit durch den Leichtbau und topologische Optimierung, die Vereinfachung der Prozesskette sowie die Umsetzung neuer Geschäftsmodelle.

Die AF wird als ein Mittel zur Reduzierung der Umweltauswirkung in Produktionssystemen gesehen, da sie beispielsweise keine produktspezifische Ausrüstung oder zusätzliche Hilfsstoffe benötigt und daher den entsprechenden Ressourceneinsatz einspart. Ferner ermöglicht die AF das Zusammenführen von Bauteilen, wobei mehrere Teile in ein Bauteil oder wenig komplexe Bauteile integriert werden. Dadurch werden die entsprechenden Fertigungsschritte, Transport, Lagerung und Verpackung reduziert, was mit einer Verringerung des Ressourcenaufwands in Produktionssystemen einhergeht. Allerdings existieren auch kritische Stimmen, die Nachteile der AF gegenüber konventionellen Fertigungsverfahren aufzeigen. Beispielsweise benötigen viele Verfahren der AF Pulver als Ausgangswerkstoff, dessen Produktionsprozesse zusätzlichen Energieeinsatz erfordern. Ebenfalls schätzen aktuelle Forschungen den spezifischen Energieaufwand der AF ungefähr ein bis zwei Größenordnungen höher als den der konventionellen subtraktiven und umformenden Fertigung ein. Zur Sicherstellung der Umweltvorteile der AF sollen daher die Umweltauswirkung und der Ressourceneinsatz der AF in der Gestaltungsphase ermittelt werden.

Ökodesign beschreibt die Integration des Nachhaltigkeitsbewusstseins in der Gestaltung von Produkten, Prozessen oder Systemen, wobei Umweltauswirkung und Ressourceneinsatz minimiert werden und gleichzeitig ein möglichst hoher Nutzen zu stiften ist. Ökodesign stellt für AF einen Schlüsselfaktor dar, um die Umweltvorteile der AF in der Gestaltungsphase zu analysieren und zu verbessern. Die vorhandenen Ansätze zum Ökodesign für AF fokussieren sich auf die Verwendung von Ökobilanzen, in dem Gestaltungslösungen durch die Sachbilanz und Wirkungsabschätzung der Prozesskette mit AF bewertet werden. Da die Ökobilanz ein vollständiges Prozesskettenmodell und detaillierte Daten zu den In- und Outputs erfordert, kann sie nur nach dem Gestaltungsprozess oder nur in einer späteren Gestaltungsphase durchgeführt werden. Weisen die Designlösungen nach der Ökobilanz Mangel auf, sind die Aktivitäten in der Gestaltungsphase zu wiederholen, was zu zusätzlichem Zeit- und Kostenaufwand führt.

Um die Aktivitäten in der Gestaltung und Bewertung näher zusammen zu bringen, kann die Bewertung der energiebezogenen Leistung als ein alternatives Bewertungsinstrument im Ökodesign für AF verwendet werden. Die energiebezogene Leistung beschreibt messbare Ergebnisse bezüglich Energieeffizienz, Energieeinsatz und Energieverbrauch eines Systems oder Prozesses und wird durch eine Energieleistungskennzahl (EnPI) ausgeprägt. Im Vergleich zu einer Ökobilanz, bei der zahlreiche Umweltauswirkungen zu ermitteln sind, werden bei der Bewertung der energiebezogenen Leistung ausschließlich energierelevante Auswirkungen betrachtet. Daher erfordert die Bewertung der energiebezogenen Leistung weder ein vollständiges Prozesskettenmodell noch die detaillierten Daten der In- und Outputs und kann früher in der Gestaltungsphase durchgeführt werden. Beim gegenwärtigen Stand der Forschung fehlt jedoch ein Ansatz zur Integration der Bewertung der energiebezogenen Leistung in das Ökodesign für AF, was als die Forschungslücke dieser Arbeit darstellt.

Die vorliegende Dissertation zielt auf die Entwicklung und Validierung eines Konzepts zum Ökodesign für AF mittels der Quantifizierung und Bewertung der energiebezogenen Leistung. Das Konzept umfasst drei Bestandteile: ein Simulationstool zur Quantifizierung des Energieaufwands der AF in der Gestaltungphase; ein Modell zur Beschreibung und Bewertung der energiebezogenen Leistung der AF; und eine Vorgehensweise zur Durchführung des Ökodesigns für AF mittels des entwickelten Simulationstools und Bewertungsmodells. Diese werden im Folgenden beschrieben.

**Simulationstool zur Quantifizierung des Energieaufwands der AF**

In der Gestaltungsphase sind Experimente zur Bemessung des Energieaufwands der AF zeit- und kostenaufwendig, da die Prozessdauer der AF variiert, je nach angewandtem Verfahren und Prozessparametern von Stunden bis hin zu Tagen. Daher zielt diese Arbeit zunächst auf die Entwicklung eines Simulationstools ab, das den Energieaufwand der AF in der Gestaltungsphase schnell und zuverlässig vorhersagt. Um dies zu erreichen, werden zunächst zwei repräsentative AF-Systeme (SLM-Maschine und FDM-Drucker) spezifiziert und die Energieflüsse zwischen den Systemkomponenten in Modellen abgebildet. Anschließend wird anhand der Energiemodelle ein Simulationstool auf der Plattform MATLAB/Simulink entwickelt, wobei der NC-Code- und Datenbank-getriebene Ansatz verwendet wird. Um die Genauigkeit und Zuverlässigkeit der Simulation nachzuweisen, werden abschließend Experimente durchgeführt und mit den Simulationen verglichen. Zur Verwendung des Simulationstools wird zunächst aus der Prozessgestaltung der AF ein Prozessparametersatz in Form eines NC-Codes erstellt und in das Simulationstool geladen. Danach berechnet das Simulationstool den Energieverbrauch anhand der Zeitdaten, die aus dem NC-Code erhoben werden, und den Leistungsdaten der AF-Systeme, die in einer Datenbank hinterlegt werden. Nach der Simulation können die Simulationsergebnisse in einer Leistungskurve visualisiert werden und die Daten in eine TXT-Datei exportiert werden.

**Modell zur Beschreibung und Bewertung der energiebezogenen Leistung der AF**

Die energiebezogene Leistung der AF beschreibt die messbaren Größen, die für Energieverbrauch, -effizienz und -einsatz der AF relevant sind und als EnPI vom Entwickler definiert werden. Basierend auf den EnPI wird im Rahmen dieser Dissertation ein Modell entwickelt, das die energiebezogene Leistung der AF beschreibt und die EnPI in drei Dimensionen konkretisiert. Die erste Dimension beschreibt originale EnPI, die vom Designer nach eigenen Anforderungen definiert werden. Bei den originalen EnPI können vier Hauptarten: direkte energetische Werte, Verhältnis von energetischen Werten, Kombination der energetischen und nicht-energetischen Werte und nicht-energetische Werte. Da die originalen EnPI unterschiedliche Einheiten besitzen und daher nicht direkt miteinander verglichen werden können, werden sie nach der Min-Max-Skalierung im Wertbereich in [0, 1] normalisiert. Die normalisierten EnPI bilden daher die zweite Dimension des Bewertungsmodells. Da die EnPI entsprechend der Anforderungen im Anwendungsszenario unterschiedliche Wichtigkeit aufweisen können, werden die EnPI nach der Methode paarweisen Vergleich gewichtet. Die Gewichtungsfaktoren werden abschließend mit den normlaisierten EnPI aggregiert, was die dritte Dimension des Bewertungsmodells bildet und die endgültige energiebezogene Leistung der AF repräsentiert.

**Vorgehensweise zur Durchführung des Ökodesign für AF**

Um die Durchführung des Ökodesigns für AF zu ermöglichen, wird im Rahmen der Dissertation eine Vorgehensweise entwickelt, die die Schritte und die dafür verwendeten Hilfsmittel beschreibt und in folgende fünf Phasen eingeteilt wird:

- **Phase 1: Situationsanalyse:** Ausgehend von einem Anwendungsszenario werden zunächst in der Situationsanalyse die Anforderungen erfasst und die funktionellen und geometrischen Merkmale des vorhandenen Produkts beschrieben. Anschließend werden die Prozessketten der konventionellen Fertigungsverfahren spezifiziert. Abschließend werden die additiven Fertigungsverfahren und -anlagen ausgewählt, die für das Anwendungsszenario geeignet sind und mit konventionellen Fertigungsverfahren aus technischer und wirtschaftlicher Perspektive verglichen und bewertet.
- **Phase 2: Topologische Optimierung:** Im Anschluss an die Situationsanalyse wird in der zweiten Phase das Produkt mittels der topologischen Optimierung gestaltet. Dafür werden zunächst der Designraum des zu optimierenden Produkts und die mechanischen Randbedingungen anhand des Anwendungsszenarios definiert. Anschließend wird eine Finite-Elemente-Analyse (FEA) durchgeführt und das Volumen mit geringen Beanspruchungen entfernt und eine neue Geometrie generiert. Basierend auf der neuen Geometrie werden die FEA und Volumenreduktion wiederholt, um eine Geometrie mit noch geringen Volumen zu erzeugen. Diese iterativen Optimierungsschleifen werden so lange durchgeführt, bis das vorgegebene Optimierungsziel (z. B., erwünschte Massenreduzierung) erreicht ist.
- **Phase 3: Gestaltung des AF-Arbeitsplatzes:** Ein AF-Arbeitsplatzes besteht aus einer AF-Anlage und den damit verbundenen Peripherien. Zur Gestaltung des AF-Arbeitsplatzes werden zunächst entsprechend der in der Situationsanalyse ausgewählten AF-Anlage die notwendigen Peripherien definiert. Anschließend wird die erforderliche Grundfläche festgelegt, in dem die AF-Anlage und die Peripherien positioniert werden. Hinsichtlich der Arbeitsabläufe für die Bedienung der AF-Anlage sowie auch der Peripherien wird abschließend das Systemlayout des AF-Arbeitsplatzes geplant.
- **Phase 4: Gestaltung des Bauprozesses:** Basierend auf dem optimierten Produkt und dem gestalteten AF-Arbeitsplatz wird zunächst ein Parametersatz für einen Bauprozess erstellt, in dem die Parameter wie Schichtdicke, Aufbaurate und Orientierung des Aufbaus definiert werden. Anschließend werden thermisch-strukturelle Simulationen des Bauprozesses durchgeführt, um die Spannung und Verformung des Bauteils aufgrund der Wärmezufuhr zu bewerten. Abschließend werden die Post-Prozesse definiert, wodurch die Oberflächenqualität und die geometrische Genauigkeit des durch AF hergestellten Bauteils verbessert werden.
- **Phase 5: EnPI-basierte Bewertung:** In der letzten Phase werden EnPI entsprechend dem Anwendungsszenario und den Anforderungen definiert und parallele Designlösungen festgelegt. In den vorherigen Phasen für die Produkt-, System- und Prozessgestaltung sind unterschiedlichen Designvariante erlaubt, was zu parallelen Designlösungen führt. Anhand des Simulationswerkzeuges und Bewertungsmodells werden die Energieaufwände und EnPI der Designlösungen quantifiziert, normalisiert und mit den Gewichtungen aggregiert. Abschließend wird durch den Vergleich der aggregierten EnPI eine optimale Designlösung ausgewählt und in der Produktionsphase eingeführt.

Um das Konzept zur validieren, werden drei Anwendungsfälle umgesetzt. Die Ergebnisse haben gezeigt, dass das entwickelte Konzept ein effizientes Instrument ist, um die Umweltvorteile der AF in der Gestaltungsphase zu ermitteln und zu gewährleisten.

# List of Abbreviations

| | |
|---|---|
| ABS | Acrylonitrile butadiene styrene |
| AM | Additive manufacturing |
| CAx | Computer-aided, x = D design, M manufacturing, P planning |
| CED | Cumulative energy demand |
| CExD | Cumulative exergy demand |
| CNC | Computer numerical control |
| DED | Directed energy deposition |
| DIN | German Institute for Standardization |
| DoE | Design of experiments |
| EBM | Electron beam melting |
| EC | European Commission |
| ECCP | European Climate Change Program |
| EEC | European Economic Community |
| EnPI(s) | Energy performance indicator(s) |
| EU | European Union |
| e.g. | exempli gratia |
| etc. | et cetera |
| FAST | Function analysis system technique |
| FDM | Fused Deposition Modeling |
| GHG | Greenhouse gas |
| i.e. | id est |
| IPP | Integrated Product Policy |
| ISO | International Organization for Standardization |
| LCA | Lifecycle assessment |
| LCIA | Lifecycle impact assessment |
| LCVD | Laser chemical vapor deposition |
| LDD | Laser direct deposition |
| LEAP | Leading Edge Aviation Propulsion |
| LMD | Laser metal deposition |
| LOM | Laminated object manufacturing |
| MRO | Maintenance, repair, and overhaul |
| NC | Numerical control |
| PLA | Polylactic acid |
| POM | Precision Optical Manufacturing |
| SA | Selective aggregation |
| SLA | Stereolithography |
| SLM | Selective laser melting |
| SLS | Selective laser sintering |
| STL | Standard tessellation language |
| UV | Ultraviolet |

# 1 Introduction

Additive Manufacturing (AM) is the general term for production processes in which materials are added to create components [ISO15c, VDI 14]. Following the commercialization of stereolithography (SLA) in the late 1980s, AM has been adopted in numerous industrial sectors, such as aerospace, manufacturing, automotive, and health care [Wohl19]. In manufacturing, AM was first applied for rapid prototyping, in which low-cost plastics are used to print product models to demonstrate their geometric features [Wohl19, Gebh16]. Today, with advances in material science and mechanical engineering, AM can be used for rapid tooling, direct manufacturing, and repair and overhaul, in which metal components can be produced to ensure the long-term functional lifespan of products [Wits16, Levy03].

In parallel with the development of AM technology, environmental issues were worsening. In 1992, the United Nations held the Earth Summit in Rio de Janeiro, where it was agreed that "(..) States should reduce and eliminate unsustainable patterns of production and consumption (…)"; in 2015, the Paris Agreement, which aims to keep the increase in the global average temperature to well below 2 °C above pre-industrial levels or to limit the increase to 1.5 °C above pre-industrial levels, was proposed [Unit15, Unit92]. To achieve these goals, manufacturing systems require cleaner production technologies with less environmental impacts. Due to its unique processing mechanism, AM is considered to have environmental benefits, as it produces less material waste and facilitates the lightweighting of products and shortening of supply chains [Baum17a, Huan16, Chen15]. However, recent studies have also argued that under certain conditions, the environmental performance of AM can be worse than that of conventional manufacturing [Baum17a, Kell17]. For example, a number of AM processes require powders or filaments as feedstock, and the production process of such feedstock requires additional energy use. During the build process, the processing time can be up to hours or days, and a longer build also leads to increased electricity consumption. To realize the environmental benefits of AM, its environmental performance should be evaluated and improved during the design phase.

A key factor for realizing the environmental benefits of AM is eco-design, which refers to any type of design in which environmental issues are considered [Peng18]. In the existing literature, *eco-design for AM* approaches mainly focus on the use of lifecycle assessment (LCA) and comprise two steps: The first step is to propose one or multiple design solutions with AM, in which innovative design tools such as topology optimization or process chain planning are applied. In the second step, the environmental impacts of the AM-specific design solutions are evaluated using LCA. Based on the LCA results, a decision can be made as to whether the AM-specific design solution should be implemented or requires further improvements [Yang19, Vanl17]. However, the implementation of LCA requires the entire process chain model with AM and detailed inventory data; hence, LCA can only be executed after the design process or in the later design stage (e.g., the designing of entire process chain). This approach to firstly design and secondly to assess the environmental performance is known as the "evaluate after design" principle, which implies a loose collaboration between design and evaluation activities. Should the LCA results indicate that the environmental performance of the design with AM is insufficient, the decisions that have already been made must be repeated, leading to an increase in development time and costs. Compared to the "evaluate after design" principle, a better approach is to perform the evaluation in the middle design stage (e.g., during product and process design), an approach known as the "evaluate during design" principle. When applying LCA in the middle design phase without a process chain model, designers need to use a lifecycle inventory (LCI) database on the assumption that the processes of their design cases are the same as or at least equivalent to the reference processes in the LCI database. However, in AM, flexible and individual design cases are very common, which can lead to deviations between the unique processes in a design case and the reference processes in an LCI database. Such deviations may lead to unreliable LCA results. Since LCA is not appropriate for the middle design stage, an alternative evaluation tool called energy performance assessment can be applied. Compared to LCA, energy performance assessment focuses only on the energy use, energy efficiency, and energy consumption of a system or process and neglects other environmental impacts [ISO14]. In addition, energy performance assessment requires neither a fully modeled process chain with AM nor detailed inventory data. The benefit of the neglection of other environmental impacts and the non-need for process chain models is that energy performance assessment can be performed much earlier in the design process.

In the existing literature, there is an absence of an approach regarding the use of energy performance assessment in eco-design for AM. To address this research gap, this dissertation proposes a holistic framework for the realization of eco-design for AM based on energy performance quantification and assessment.

# 2 State of the Art

This chapter describes the theoretical background of AM and existing approaches related to the research focus of this dissertation. The origin and applications of AM, as well as the associated terminology and processes, are introduced in Chapter 2.1. Thereafter, the environmental properties of AM are characterized in Chapter 2.2, in which the benefits and challenges of AM in terms of resource efficiency and sustainability improvement are explained. Chapter 2.3 presents the definition and concept of eco-design as well as its importance for improving the environmental performance of AM. Existing approaches related to eco-design for AM are described in Chapter 2.4 and evaluated in Chapter 2.5, based on which the research gap addressed in this dissertation is identified.

## 2.1 Additive Manufacturing (AM)

### 2.1.1 A brief history of AM and terms

#### *2.1.1.1 Timeline of the development of modern AM processes*

The history of AM can be divided into three periods: *prehistory*, dating from the 1860s to the 1960s, in which objects were manually constructed layer by layer without the use of any cutting tools or computers; *precursors*, ranging from the 1960s to the mid-1980s, in which AM technologies encompassed all features of modern AM processes except for the use of computer interfaces; and *modern processes*, which date from the mid-1980s and are characterized by commercialized AM processes that are fully supported by computers and information technology [Bour16]. Today, AM technology applications are in the era of *modern processes*, a brief timeline of which is depicted in Figure 2-1.

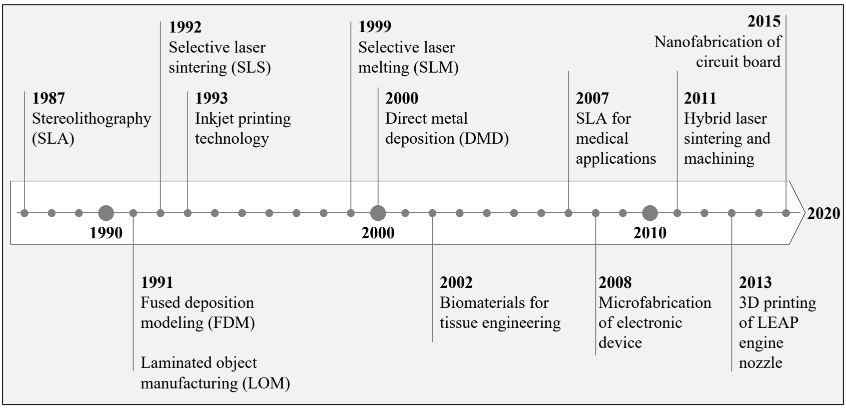



Figure 2-1: A brief timeline of the development of modern AM processes (based on [Wohl19])

In 1987, 3D Systems introduced the first commercial SLA system to the market, which represents the advent of modern AM technology [Bour16, Hull84]. SLA belongs to *vat photopolymerization*, which is one of the seven categories of AM processes introduced in Chapter 2.1.4 [ISO15c]. In the following years, different SLA systems were released by companies from Japan, the USA, and Germany [Wohl19].

In 1991, Stratasys proposed an FDM system, and Helisys introduced a laminated object manufacturing (LOM) system [Feyg95, Crum89]. FDM and LOM respectively represent two AM process categories: *material extrusion* and *sheet lamination* [ISO15c].

In 1992, DTM (today a part of 3D Systems) released a selective laser sintering (SLS) system, which belongs to *powder bed fusion*, one of the seven categories of AM processes [ISO15c, Deck86].

In 1993, the Massachusetts Institute of Technology (MIT) invented a technique for bonding ceramic powders using liquid binder through an inkjet head, which is commercialized by Soligen [Cima92]. This technology belongs to the AM process category of *binder jetting* [ISO15c]. In the following years, different companies proposed similar inkjet head-based AM processes, in which the build material (e.g., wax) is directly dripped onto a platform through an inkjet head, instead of adhering the powder with a binder agent [Wohl19]. These processes fall under the AM process category of *material jetting* [ISO15c].

In 1999, SLM, which is a process similar to SLS, was introduced. The main difference between SLS and SLM is that the latter completely melts the powder, while SLS only partially melts the powder [Mein99]. Hence, metal parts produced by SLS must be heat-treated, whereas doing so is not necessary for metal parts made using SLM.

In 2000, Precision Optical Manufacturing (POM) released a direct metal deposition (DMD) system, which uses laser and metal powder to produce and repair products [Mazu00]. DMD belongs to the AM process category named *directed energy deposition*. Other directed energy deposition processes, however, employ different materials and heat sources. For example, an electron beam can be used to replace a laser beam, and a metal wire can replace metal powder [Wu18, Murr12].

Previously, AM was mainly applied for rapid prototyping, in which plastic prototypes are printed to demonstrate the geometrical features of a product [Wohl19, Gebh16]. Today, the applications of AM have been extended from prototyping to the direct manufacturing of functional parts and tools [Gebh16], and industries such as aerospace, biology, electronics, and construction have adopted AM. For example, in 2002, Envisiontec began offering the Perfactory and Bioplotter machines for printing biomaterials in tissue engineering [Chua17]. In 2007, Advanced Laser Materials introduced a high-strength and high-temperature-resistant SLA resin for medical use [Butt19]. In 2008, Nuvostronics released PolyStrata microfabrication technology for producing electronic devices [Wohl19]. In 2015, Nano Dimension introduced the Dragonfly 2020 system, which is used for printing electrical circuits [Davi15].

With the expansion of the fields of application of AM, the combination of AM with conventional manufacturing represents an important advance in state-of-the-art manufacturing technologies. In 2011, Matsuura released the LUMEX Avance-25 machine, in which laser sintering and computer numerical control (CNC) machining are combined [Sriv20]. In the following years, other companies released hybrid AM systems combining laser wielding deposition and CNC machining [Merk16]. The integration of AM with conventional machining processes enables the production of complex and versatile components.

In 2013, General Electric (GE) decided to use fuel nozzles produced by AM on Leading Edge Aviation Propulsion (LEAP) engines, the nozzles of which are constructed using AM and are single components, whereas previous nozzles were 20-piece assemblies [Wohl19]. The new nozzles made by AM are lighter and much more durable than the previous nozzles, which indicates the successful application of AM technology in modern industries.

#### *2.1.1.2 AM terms and synonyms*

According to the standard ISO/ASTM 52900, the term "additive manufacturing" is defined as a " (..) process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies (…)" [ISO15b]. Similarly, the German standard VDI 3405 defines an AM process as a "(..) manufacturing process in which the workpiece is built up in successive layers or units (…)" [VDI 14]. The equipment used for AM purposes, including the hardware and software accessories used to carry out build cycles, is defined as an AM machine. Furthermore, an AM machine and its auxiliary units comprise an AM system [ISO15b].

As depicted in Figure 2-2, many synonyms are used in addition to the term AM [Bour16]. The most widespread synonym for AM is "3D printing," which implies that an AM process is "(..) 3D analog to ubiquitous 2D printers (…)" [Bour16]. To better facilitate the development of AM technologies, the ASTM F42 Technical Committee on Additive Manufacturing held a meeting on January 14, 2009, in West Conshohocken, Pennsylvania, in which the term "additive manufacturing" was formally selected as the name for processes involving joining materials to create parts [Bour16]. Additionally, the term AM has been adopted and embraced by the ISO Technical Committee TC 261, which is working on the development of standards for AM. Today, the term AM has been widely adopted by research communities.

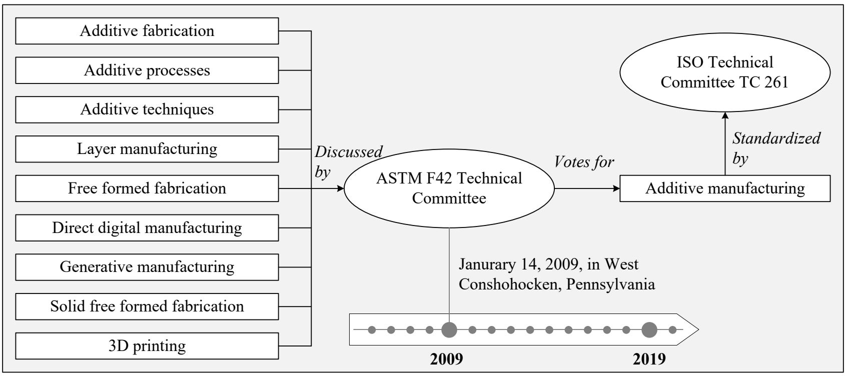



Figure 2-2: Synonyms of AM (according to [Bour16])

#### *2.1.1.3 Difference between AM and conventional manufacturing*

A manufacturing process can be regarded as a combination of operations for the production of geometrically defined solid bodies (*German*: " (..) Verfahren zur Herstellung von geometrisch bestimmten festen Körpern (…)") [DIN03]. There are three fundamental methods for the shaping of material into a physical form: *formative shaping*, in which the desired geometry is created by applying pressure (e.g., bending) to a body of raw material; *subtractive shaping*, in which the desired geometry is created by the selective removal of materials (e.g., milling); and *additive shaping*, in which the desired geometry is created through the successive addition of material [ISO15b]. The essential difference among these methods is the volume change that a workpiece undergoes [Gebh16]. For example, assuming a constant material density, the volume of a workpiece before and after the shaping of material can be regarded as $V_0$ and $V_1$, respectively, as depicted in Figure 2-3. In subtractive manufacturing, $V_1$ will be smaller than $V_0$ due to the material removal. In formative shaping, $V_1$ will be equal to $V_0$, as material is neither removed nor added. It is only in additive shaping that $V_1$ will be greater than $V_0$, as the material will be applied in an additive fashion. Thus, by observing the volume change of the workpiece during the shaping process, AM processes can be distinguished from conventional manufacturing processes.

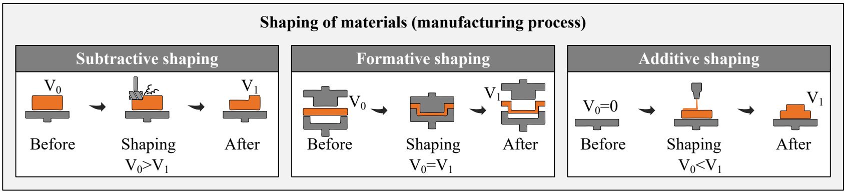



Figure 2-3: Distinguishing between AM and conventional manufacturing

In addition to the shaping of materials, AM processes demonstrate the following technical characteristics during their application:

- **Preparation of a computer-aided design (CAD) model and parameter set**: Before a build task is performed with an AM machine, a digital parameter set is needed. To generate such a parameter set, AM pre-processing software is used, in which the CAD model of a component can be sliced and process parameters such as layer thickness and print speed can be defined. Finally, the parameter set containing all process information can be directly used to start a build task [Gebh16].
- **Wide range of materials**: Today, AM is able to process basically any type of material, including polymers, metals, composite materials, and ceramics [Krut98]. Feedstock should be produced in different forms for different AM processes; for example, SLM requires powders, while FDM applies filaments.
- **Absence of cutting or clamping tools**: The build of layers during AM does not require the cutting or clamping tools used in conventional subtractive processes. Hence, theoretically, AM can create a part in all possible orientations without any clamping problems [Gebh16].
- **Need for support structure**: A support structure is needed for a variety of AM processes. This structure has two purposes: preventing the collapse of molten layers (particularly when creating large overhanging surfaces) and dissipating heat to prevent high residual stresses [Vayr12]. The support structure will need to be removed after the completion of a build task.
- **Enabling design freedom**: Due to its unique processing mechanism, AM enables greater design freedom, which can be expressed in four aspects: use of complex geometry such as hollow bodies and lattice structures; use of customized geometry directly from individual customers; part consolidation and integration of features into single parts to avoid assembly issues; and elimination of the constraints imposed by conventional manufacturing [Gibs15].
- **High material performance**: Today, the relative density of the parts produced by laser AM processes ranges from 99% to 100%, and metal parts produced by AM can offer

equivalent or even superior material properties when compared to parts produced with conventional casting or wrought processes [Wohl19]. For example, parts produced by SLM have a higher yield and ultimate strength than conventionally wrought parts [Zhan18].

### 2.1.2 Industrial AM applications

The application of AM can be generally divided into three categories: *rapid prototyping*, in which AM is used to produce prototypes, concept models, or other parts, but not products; *rapid manufacturing*, in which AM is used to produce final products or tools that provide long-term functionalities; and *rapid maintenance, repair, and overhaul* (MRO), in which AM is used to repair or remanufacture defective parts [Gebh16, Wits16]. In addition, the three categories can be allocated to different phases of the lifecycle of an AM product, and each category features application subcategories, as depicted in Figure 2-4 and described in the following subsections.

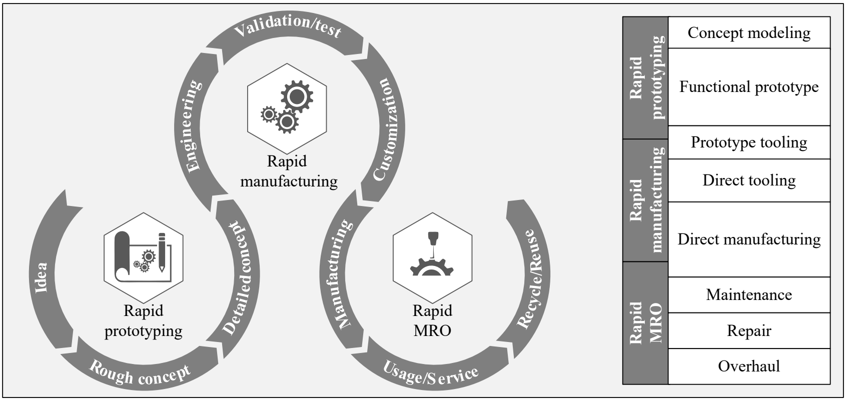



Figure 2-4: Classification of the fields of application of AM (based on [Gebh16, Wits16])

#### *2.1.2.1 Rapid prototyping*

Rapid prototyping was the first application area of AM technology after the AM process was commercialized in the 1980s. Rapid prototyping can be used during the idea, concept, and engineering phases of a product lifecycle, in which physical samples and models are rapidly fabricated to demonstrate the concept, shape, functionality, or other basic features of a product [Liou19]. Prototypes that demonstrate a product concept are also called *show-and-tell models,* while prototypes used to verify one or few functions of a product or a tool are called *functional prototype* or *prototype tool* [Gebh16]. Figure 2-5 depicts five examples of AM prototypes in different industrial areas. It can take weeks or months to produce a prototype using conventional prototyping methods such as molding or handcrafting, while, when using AM, a prototype can be printed in hours or days.

Compared to conventional methods used to make prototypes, such as molding, the absence of product-specific tools and the ability to directly produce a prototype from a CAD model when using AM enable the elimination of the stages in which tools are prepared and drawings created. Consequently, the development costs and the time to market can be significantly reduced [Liou19]. Moreover, to further save costs and reduce the time required for product development, the use of simple printers and low-priced materials such as paper or plastics is preferred in rapid prototyping. AM processes related to low-priced materials and AM systems include, for example, SLA, selective sintering of polymer powders, layer lamination, FDM, inkjet printing, and powder-binder jetting [Gebh16, Ponf14].

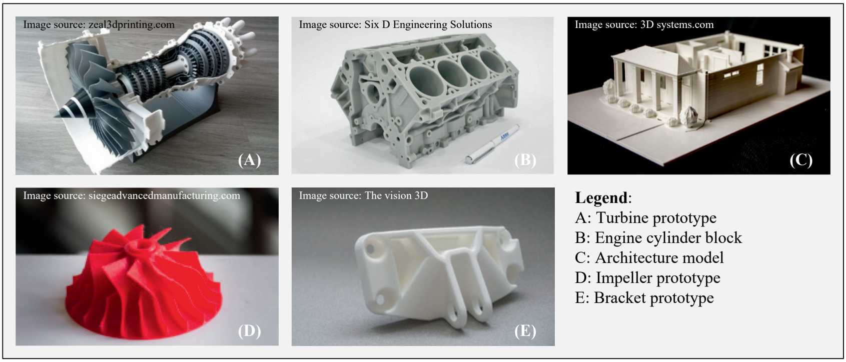



Figure 2-5: Examples of prototypes made by AM

#### *2.1.2.2 Rapid manufacturing*

From the 1990s to the 2000s, the application field of AM was extended from rapid prototyping to rapid manufacturing, in which end-use products or tools providing long-term functionalities are produced with AM [Levy03]. The direct production of final products is called *direct manufacturing*, whereas the direct production of tools is called *direct tooling* [Gebh16]. Rapid manufacturing is related to the engineering, validation/testing, customization, and manufacturing phases of a product lifecycle. Since rapid manufacturing is intended to produce products that can be used in the long-term, the materials used therein include engineering polymers, metals, ceramics, and composites [Levy03]. The main advantage of AM when compared to conventional manufacturing is the increased design freedom, in which novel geometrical structures can be applied in a product design. Figure 2-6 shows five examples of tools and products produced with AM, in which topology optimization and lattice structure are applied. Were these items to have been produced using a machining process, two problems may have arisen: first, a high amount of material would have been removed, leading to a high waste of material, and, second, it would not have been possible to insert a cutting tool into the interiors of the items to shape their internal structures. Had they been produced using a casting process, it may have proven extremely expensive or impossible to produce the casting dies that would have been used to produce them.

The AM processes related to rapid manufacturing are laser metal deposition (LMD), SLM, electron beam melting (EBM), SLA, cold spray, sheet lamination, and other AM processes that can be used to produce metals, composites, and ceramics. Since rapid manufacturing enables the creation of products offering long-term full functionality, the relevant systems and materials are more expensive overall than the systems and materials used for rapid prototyping. For example, the prices of modern SLM and LMD machines can range up to millions or tens of millions of euros, while the prices of FDM printers used for prototyping can be under thousands or even hundreds of euros [Wohl19].

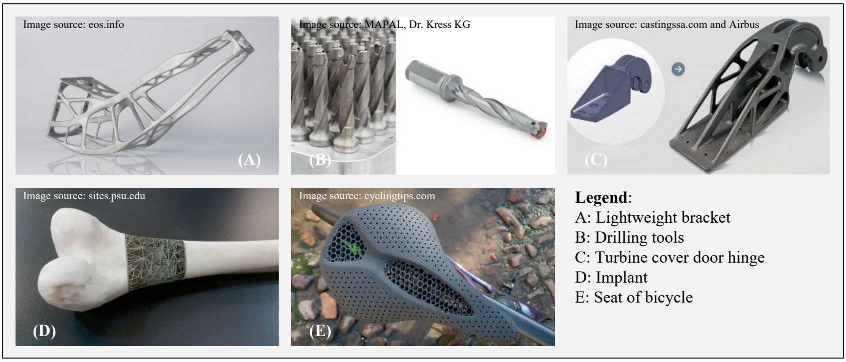



Figure 2-6: Examples of products and tools made by AM

### *2.1.2.3 Rapid maintenance, repair, and overhaul*

Compared to rapid prototyping and rapid manufacturing, in which a new component is created, rapid MRO aims at restoring the functionality of an existing part and can be allocated to the use, service, and end-of-life phases of an AM product lifecycle [Bour09]. A key motivation for the use of rapid MRO is enabling a circular economy in which a defective product is repaired or remanufactured with AM to prolong its current use phase or to add a new use phase after that product's end-of-life [Wits16]. One of the most relevant AM processes for rapid MRO is LMD, which has three advantages compared to the use of conventional welding process to repair components: *low heat input*, which leads to low distortion; *superior microstructures*, leading to superior material properties; and *stable and repeatable energy input of laser beam*, which enables better reproducibility and reliability of the product quality [Graf12]. Figure 2-7 shows an example in which a defective gear tooth has been repaired by LMD. First, the defective gear tooth is removed by machining. Second, the removed gear tooth is roughly generated by LMD. Finally, using machining once again, the contour of the gear tooth is created and the functionality of the gear is thus restored.

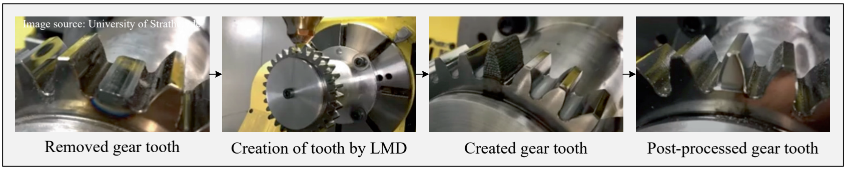



Figure 2-7: Example of the application of rapid MRO

## 2.1.3 AM materials

Today, *polymer* and *metals* are the two main categories of AM materials [Wohl19]. Nevertheless, other materials, such as composites, ceramics, paper, and wood, are also available. The feedstock for different AM processes should be produced in different forms. For example, Figure 2-8 presents examples of polymer filaments, titanium wires, copper sheets, photopolymer liquid, and steel powders, which are respectively used for extrusion, directed energy deposition, sheet lamination, vat photopolymerization, and powder bed fusion. Note that in comparison to AM, conventional subtractive and formative processes are relatively less sensitive to the shape of feedstock. Therefore, the production of feedstock for AM may face challenges that conventional manufacturing processes do not. For example, in powder-based AM processes, powders with different particle sizes require different process parameter settings, and recycled and virgin powders may exhibit different performance in terms of final material quality [Cord19, Zhan19].

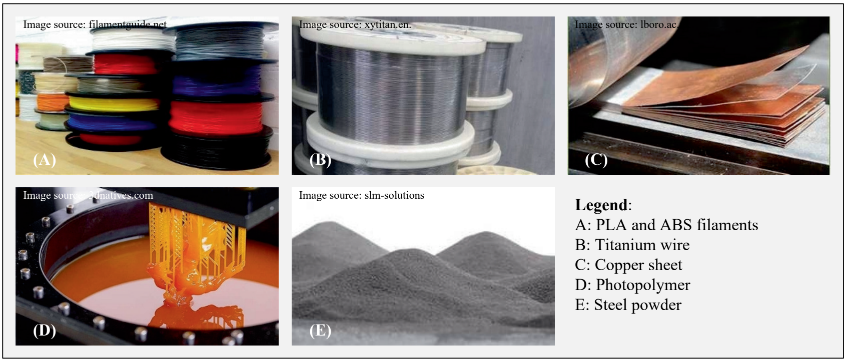



Figure 2-8: Examples of AM materials

Feedstocks used for AM processes can be classified as *solid*, *paste*, *liquid*, *aerosol*, and *gas*, as depicted in Figure 2-9 [Gebh16]. Different materials require different processing principles and are suitable for different AM processes, and they are described in the following paragraphs [Wohl19, Gebh16, ISO15c].

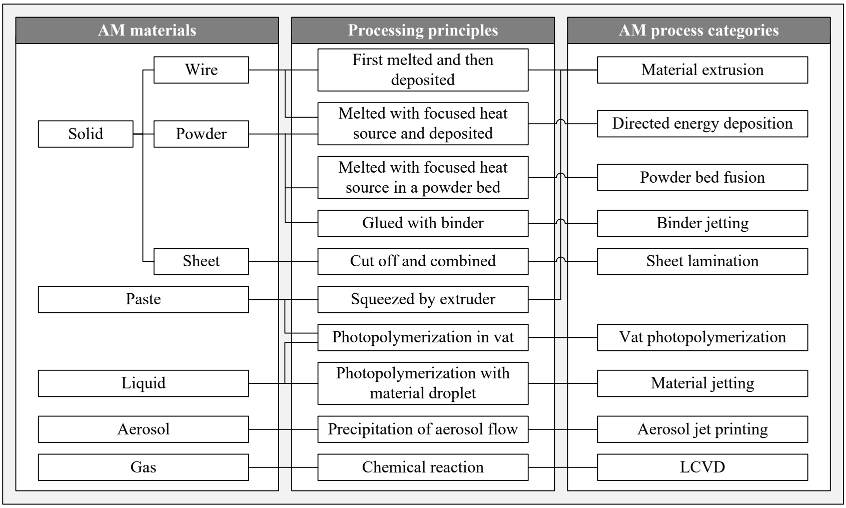



Figure 2-9: Classification of AM materials (according to [Wohl19, Gebh16, ISO15c])

- **Solid**: Solid material can be further divided into *wire*, *powder*, and *sheet* (or foil/plate). *Wire* can be used for material extrusion and directed energy deposition. For material extrusion, the plastic wire is first melted and then deposited by nozzles onto a platform. For directed energy deposition, a high-energy beam (e.g., a laser beam) creates a molten pool into which the metal wire is continuously fed and melted into layers. *Powder* can be used for three types of AM processes: directed energy deposition, in which powder is melted by a focused energy beam; powder bed fusion, in which a focused energy beam scans a selected area of a powder bed; and binder jetting, in which powders are glued by binders. *Sheet-form* materials are used for sheet lamination, in which sheets are cut off from lasers or cutting tools and combined to form 3D objects.
- **Paste**: *Paste-form* material can be used for material extrusion and vat photopolymerization. Usually, material extrusion involves the use of a heating core to melt plastic filaments and then extrude them. However, the extruded materials are not limited to thermoplastics, and semi-liquid materials such as gels or slurries can be squeezed directly without any heating. For vat photopolymerization, a photo-curable paste can also be used in addition to a liquid.
- **Liquid**: Photo-curable *liquids* are mainly used for vat photopolymerization and material jetting. The difference between vat photopolymerization and material jetting is that a liquid can be photopolymerized either in a vat or as droplets dispensed through inkjet heads.
- **Aerosol**: An AM process called *aerosol jet printing* deposits a flow of aerosol (the particle sizes of which are up to 200 nm) with a diameter between 1 and 5 μm onto a substrate to create parts after the precipitation of the *aerosol* flow [Opto20, Gebh16].
- **Gas**: An AM process involving the use of *gas* is called *laser chemical vapor deposition* (LCVD), in which laser beams are used to activate a chemical reaction between an aluminum gas ($AlH_3N(CH_3)_3$) and an oxygen-containing gas ($N_2O$). The result of the chemical reaction is a solid aluminum oxide that can be combined to generate parts [Gebh16, Lehm94].

### 2.1.4 AM processes and system characteristics

The ISO 17296-2 standard defines seven categories of AM processes [ISO15c]. The following subsections describe the system features and technical characteristics of these processes.

#### *2.1.4.1 Vat photopolymerization*

*Vat photopolymerization* refers to AM processes in which "(..) liquid photopolymer in a vat is selectively cured by light-activated polymerization (…)" [ISO15c]. The feedstocks used for *vat photopolymerization* include light-curable liquids, pastes, resins, and other photopolymers. In addition, *vat photopolymerization* can also be used to process metals, ceramics, or composites if they are made into particles and filled with photopolymers [Well15].

Figure 2-10 illustrates a *vat photopolymerization* system, in which a liquid photopolymer is filled in a vat. To create a layer, an ultraviolet (UV) light-curing source (typically UV radiation from a laser or a lamp) scans a selected area of the vat, where the liquid is solidified into a layer. After a layer is created, the platform will be leveled down to allow another processing loop to be executed. After the build task is finished, support material should be removed, and post-processes such as post-curing by further UV exposure may be required.

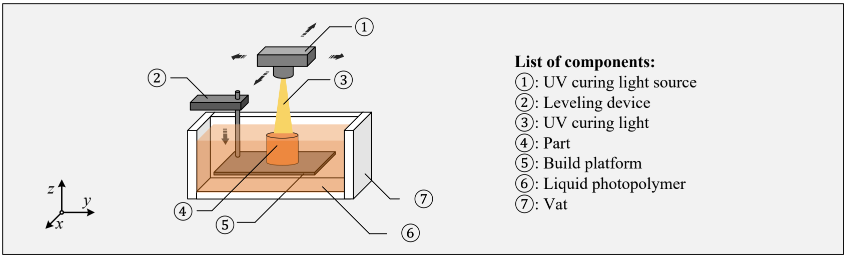



Figure 2-10: Components of a vat photopolymerization system (according to [ISO15c])

Compared to other AM processes, three advantages of *vat photopolymerization* are high geometrical accuracy, high surface quality, and processing flexibility (e.g., it is capable of processing components of sizes varying from 100 nm to 1.5 m [Gibs15]). However, the main disadvantage of *vat photopolymerization* is the limited choice of materials. The most commonly used materials are acrylates and epoxies; while other material families are photo-curable, none of them have achieved commercial success [Gibs15].

### *2.1.4.2 Material jetting*

*Material jetting* describes an AM process in which "(..) droplets of build material are selectively deposited (…)" [ISO15c]. The commercialized feedstock for *material jetting* includes waxy polymers and acrylic photopolymers, while other materials, such as metals and ceramics, have not been commercialized yet but have demonstrated high potential for future applications [Gibs15].

Figure 2-11 presents a schematic diagram of a *material jetting* system in which two inkjet nozzles respectively deposit droplets of build materials and support materials on a platform. During the print process, a UV light cures the droplets into solid layers. After a layer is built, the platform moves downwards to allow the next build cycle to begin. After the build process is finished, the support structure should be removed, and post-curing may be required.

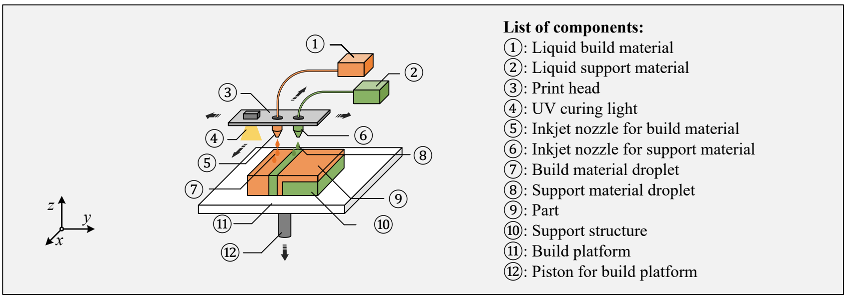



Figure 2-11: Components of a material jetting system (according to [ISO15c])

Compared to other AM processes, *material jetting* is relatively complex because it involves droplet problems (i.e., formation of liquid materials, formulation of droplets, and difficulty of controlling the droplets [Gibs15]). The primary advantages of *material jetting* include low cost, a high build rate, and the possibility of using multiple materials and printing colors. Compared to other polymer AM processes such as SLA and FDM, the drawbacks of *material jetting* are the limited choice of materials and limited geometrical accuracy for larger parts [Gibs15].

### 2.1.4.3 Binder jetting

*Binder jetting* refers to AM processes in which "(..) a liquid bonding agent is selectively deposited to join powder materials (…)" [ISO15c]. *Binder jetting* is similar to *material jetting* in that both approaches involve the use of inkjet heads to deposit droplets of liquid material. The difference between them is that *material jetting* prints a build material, while *binder jetting* only prints a binder agent. The powders used for *binder jetting* can be metals, ceramics, polymers, or composites. Therefore, *binder jetting* is one of the most versatile AM processes, as it is capable of processing different materials [Wohl19, Well15].

Figure 2-12 shows the main system components of a *binder jetting* system in which an inkjet print head deposits a bonding agent to a powder bed to create layers and parts. Between two build cycles, the powder container and powder bed move upwards and downwards, respectively, to enable the powder spreading. After the build process, the support structure should be removed, and post-thermal treatment may be required.

The benefits of *binder jetting* are the ability to use wide range of materials and the capability to combine powder materials with additives in binders, printing colors, and slurries with higher solids loadings, leading to a higher material density compared to the components made with *material jetting* [Gibs15]. However, *binder jetting* also has drawbacks, such as requiring additional steps for powder spreading, which leads to long processing times and limited geometrical accuracy and surface quality. Moreover, for producing metals and ceramics, additional sintering or infiltration with a melted material is required to consolidate the material [ISO15c].

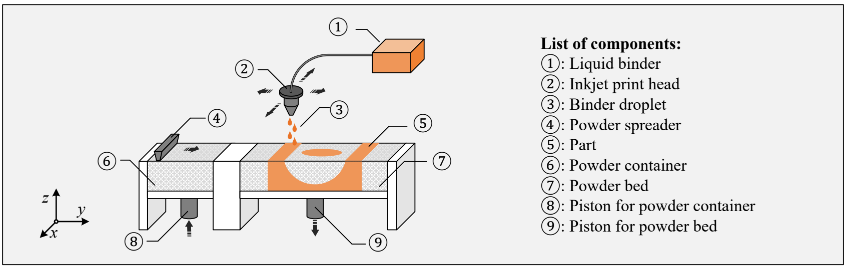



Figure 2-12: Components of a binder jetting system (according to [ISO15c])

### 2.1.4.4 Powder bed fusion

*Powder bed fusion* is defined as an AM process in which "(..) thermal energy selectively fuses regions of a powder bed (…)" [ISO15c]. *Powder bed fusion* is a process similar to *binder jetting* in that both involve applying powder beds. The difference between them is that *powder bed fusion* binds powders using thermal energy, whereas *binder jetting* uses a bonding agent to combine powders, and no thermal energy is inputted to the powder bed. The thermal energy source of *powder bed fusion* can be a laser beam, electron beam, or an infrared lamp. *Powder bed fusion* is suitable for processing polymers, metals, ceramics, or powders being filled with binder matrix.

Figure 2-13 presents a schematic diagram of a *powder bed fusion* system in which a laser beam controlled by a deflection mirror is used to scan a selected area of a powder bed. After a layer is scanned, the powder container and powder bed move upwards and downwards, respectively, to enable the spreading of the powder. After the build task is finished, the support structure should be removed. Post-heat treatment is required for some processes, such as SLS, in which the powder is partially melted. For other processes that fully melt powders, such as SLM and EBM, heat treatment is not needed.

The advantages of *powder bed fusion* when compared to other AM processes are the wide range of materials that can be used, excellent material performance, capability to process very small features, high geometrical accuracy, and high surface quality. These benefits are also the reasons why *powder bed fusion* has become one of the most used AM process for producing metal parts [Wohl19, Gibs15]. The primary drawbacks of *powder bed fusion* include long processing times, high investment costs, and residual stress due to the high energy input.

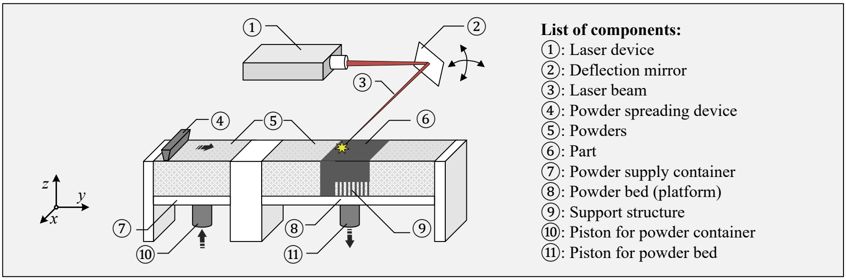



Figure 2-13: Components of a powder bed fusion system (according to [ISO15c])

### *2.1.4.5 Material extrusion*

*Material extrusion* refers to processes in which "(..) material is selectively dispensed through a nozzle or orifice (…)" [ISO15c]. Due to the relatively simple nature of this process and the low prices of the machines used for it, *material extrusion* has been widely used for polymer prototyping [Wohl19]. In addition, *material extrusion* can also be used to process structural ceramics or even metals if they are in particles and filled with a binder matrix [Müll19].

Figure 2-14 presents a schematic diagram of a material extrusion system, in which two nozzles extrude build material and support material, respectively, and the platform moves downwards between each two build cycles. After the build task, the support structure should be removed.

Compared to other AM processes, *material extrusion* has a number of benefits, such as the wide range of materials that can be used, the relatively low prices of the machines used for this process, and flexibility in terms of processing parts of different sizes. However, *material extrusion* is subject to disadvantages such as limited geometrical accuracy due to the shrinkage of material and limited surface quality [Chua10].

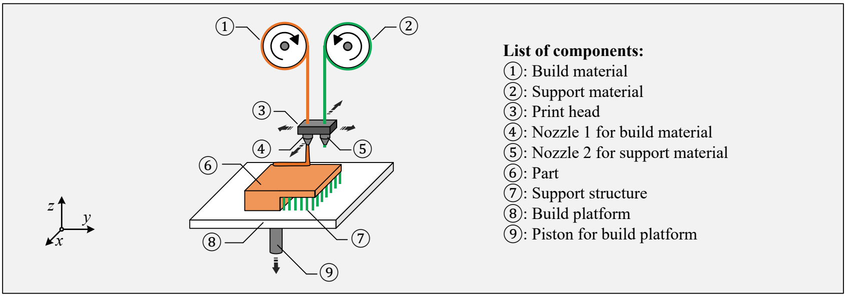



Figure 2-14: Components of a material extrusion system (according to [ISO15c])

#### 2.1.4.6 *Directed energy deposition*

*Directed energy deposition* is defined as an AM process in which "(..) focused thermal energy is used to fuse materials by melting as they are being deposited (…)" [ISO15c]. *Directed energy deposition* enables the production of metal parts with long lifespans, and it is widely used for rapid manufacturing and MRO [Ponf14]. Two types of feedstock for *directed energy deposition* are powders and wires, and three typical thermal energy sources are laser beams, electron beams, and plasma arcs [ISO15b].

Figure 2-15 presents a schematic diagram of a *directed energy deposition* system, in which a laser beam creates a molten pool on the substrate and a metal wire is fed into the molten pool. During the processing, the build platform can move in different directions, which means that the material processing and platform leveling can be executed simultaneously. Moreover, a rotary table can be used as the platform of a *directed energy deposition* system to achieve a higher degree of freedom during the build [Gibs15]. Today, the accessories used for *directed laser deposition* such as deposition head can be integrated to conventional milling systems to enable hybrid additive-subtractive manufacturing [DMG18].

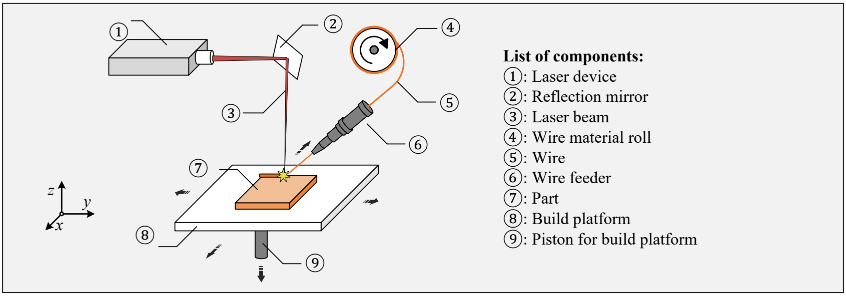



Figure 2-15: Components of a directed energy deposition system (according to [ISO15c])

*Directed energy deposition* offers benefits such as no additional time being required for spreading powders (compared to powder bed-based AM processes), the capability to control the microstructure and material composition, high material density, the ability to use multiple materials, and the capability of producing parts with large sizes [Wohl19, Gibs15]. However, *directed energy deposition* has certain drawbacks, such as low geometrical accuracy, a limited capability to produce small features, and limited surface quality. To ensure the quality of end parts, post-processing such as milling and drilling should be required. In addition, depending on the materials used, post-heat treatment may be required to relieve the residual stress of materials [Gibs15].

#### *2.1.4.7 Sheet lamination*

*Sheet lamination* is defined as an AM process in which "(..) sheets of material are bonded to form an object (…)" [ISO15c]. The feedstock of *sheet lamination* includes metal foil, paper, polymer, and composite sheets made of metal or ceramic powders with a binder matrix. The binding mechanisms are typically gluing or adhesive bonding, thermal bonding, clamping, or ultrasonic welding [Gibs15].

Figure 2-16 shows the main components of a *sheet lamination* system, in which sheets are pressed together by a roller and then cut by a laser beam. In practice, a knife or a milling tool could also be used to cut the sheets. After a layer is added, the waste take-up roller rotates to enable the feeding of a new layer from the material supply roll. During the build, the frame around the component is also cut into small pieces, which makes it easier to conveniently remove them after the build process. Finally, post-processing such as sintering, infiltration, or heat treatment may be required to solidify the material.

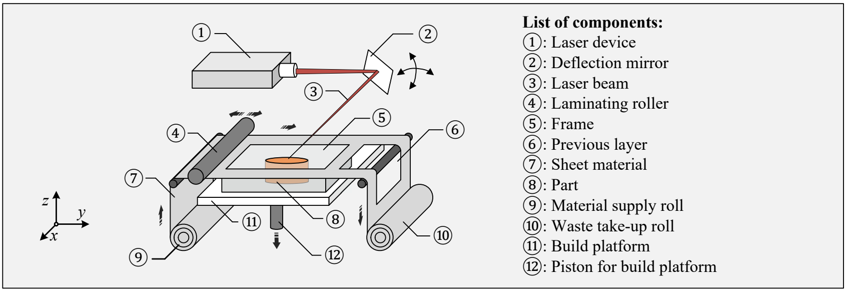



Figure 2-16: Components of a sheet lamination system (according to [ISO15c])

The benefits of *sheet lamination* comprise the ability to use a wide range of materials, easy and flexible operation, the capability to combine different material layers, no need for supports, capability for larger layer thickness, and fast build rates, as only the outline of a layer is cut instead of melting or curing a cross-sectional area of a layer [Gibs15]. The main disadvantage of *sheet lamination* is the difficulty of removing the frame and blocks surrounding the component [Gebh16].

#### *2.1.4.8 Direct write*

Note that in Sections 2.1.4.1 to 2.1.4.7, the seven AM process categories identified in ISO 17296-2:2015 were described. However, in addition to these seven categories, GIBSON ET AL. have proposed another category called *direct write*, which refers to processes used to create small-scale structures or electronics whose feature resolutions are smaller than 50 µm [Gibs15]. For example, aerosol jet printing and LCVD (shown in Figure 2-9) do not match the definitions of any of the seven AM process categories and thus cannot be included in ISO17296-2:2015.

Nevertheless, when one considers that they can produce micro features, they can be allocated to the *direct write* category [Gibs15].

*Direct write* evolved from *material extrusion* when the US Defense Advanced Research Projects Agency (DARPA) noted that the *material extrusion* process could be further developed to produce electronic circuitry and mesoscale devices such as capacitors, conductors, insulators, and batteries [Gibs15]. With technological progress, *direct write* processes have also become capable of producing microthermal, electrical, chemical, and biological components [Gibs15]. Today, based on the processing principle, it is possible to identify six types of *direct write* processes: the *ink-based process*, in which tailored inks (e.g., inks with nanoparticles) are printed to create objects (aerosol jet printing belongs to this type); the *laser transfer process*, in which a laser beam is used to heat, melt, or ablate materials on a micro-scale; *thermal spray*, in which materials are accelerated to high speeds and deposited on a substrate; *beam deposition*, in which high-energy beams (e.g., laser or electron beams) are used to produce solid material by condensation, chemical reaction, or conversion of material from a vapor state (LCVD belongs to this type); *liquid-phase direct deposition*, in which thermal or electrical energy is used to convert liquid-phase materials into solid materials; and *beam tracing processes*, in which high-energy beams are used to trim layers into prescribed cross-sectional geometries and bond them together (in a process similar to that of sheet lamination) [Gibs15].

### 2.1.5 Trends and challenges of AM

#### *2.1.5.1 Trends and potential of AM*

While it has existed for over 30 years, AM has recently drawn more attention from research communities and industries [Atta17]. According to *Wohlers Report 2019*, the number of worldwide AM system manufacturers increased from 33 in 2012 to 177 in 2018 (a factor of 5.36 times [Wohl19]). Based on current research on AM in terms of technology development and applications, the following trends can be observed:

- **Shift of focus from prototyping to manufacturing and MRO**: AM was originally developed to create models and prototypes. Since the potential of rapid prototyping has been well explored over the last decades, the recent focus of AM applications has shifted from prototyping to rapid manufacturing and MRO [Bech15, Bour09]. Users expect AM to produce parts that can offer long-term functional use, as opposed to producing show-and-tell models without or with only limited functionality. For AM providers, advances in AM systems (e.g., the ability to use stable and high-power ytterbium-lasers [Lee17]) and materials (e.g., the ability to use powders such as steel, aluminum, or titanium [Zhan18]) ensure that parts produced by AM can offer equivalent or even superior performance to those created using conventional casting or wrought processes.
- **Adoption in cross-industrial areas**: Due to its ability to use diverse range of materials and technologies, AM has been applied in different industries [Atta17]. For example, while the aerospace and automotive industries have adopted AM to produce lightweight parts to reduce fuel consumption, the dental field has applied AM to create customized dental crowns, the electronics industry uses AM to print circuit boards, the architecture industry uses AM to print houses through squeezing concrete, and the food industry employs AM to print chocolate models [Kary19, Vale19, Wohl19]. It is anticipated that AM will be used in an increasingly wide range of industrial areas in the future [Kohl16].

- **More design freedom:** On the material level, AM enables the use of multiple materials and customized materials, surfaces, or textures, while, on the part level, AM can be used to optimize the topology and cellular surface of a part to simultaneously improve the component's functional performance and reduce its material use [Tang16a, Thom16b, Ford14]. Moreover, AM enables part consolidation, in which an assembly with a number of components can be redesigned into a single complex part [Yang15]. As an additional benefit, it is possible to reduce the number of assembly processes and the corresponding secondary processes (e.g., transport and storage). Eventually, AM has the potential to allow new business models to be designed based on the benefits that this approach offers on the material, product, and process chain levels [Thom16b]. For example, AM enables mass customization, in which low-priced and high-quality products are produced by AM and offered to the market [Chen15].
- **Merging with conventional subtractive manufacturing**: Although AM represents the opposite of conventional subtractive manufacturing, it is not intended to replace subtractive manufacturing [Atta17]. On the contrary, it has been observed that the latest AM processes are being merged with conventional subtractive manufacturing (e.g., milling processes) to achieve a higher degree of manufacturability [Zhu13]. AM can produce complex parts that cannot be produced by subtractive processes, while subtractive processes can produce components with greater dimensional accuracy and surface quality than AM. Therefore, the integration of AM with subtractive manufacturing in one system implies the merging of the respective advantages of AM and subtractive manufacturing [Sosh17].
- **Reorganization of production networks and supply chains**: AM enables shorter and simpler supply chains, localized production networks, innovative distribution models, and new collaborations between designers and users [Ford16]. Since products designed for AM tend to have fewer parts and require less materials and fewer actors in their production, production facilities can be established close to the market. Shorter supply chains and decentralized production also imply the reduction of logistics costs. Therefore, in the future, when referring to AM, the term "logistics" may refer more to delivering digital design files rather than to complex and heavy assemblies or products [Ford16]. Moreover, decentralized production with AM may give rise to a more non-linear distribution model and more collaborations among designers, producers, and local customers [Chen15].
- **Improved sustainability**: Based on the benefits it offers on the product, process chain, and business model levels, AM will likely eventually lead to more sustainable societies [Ford16]. For example, at the economic level, AM reduces manufacturing costs by preventing material waste or over-production. By allowing companies to offer customer-oriented products or solutions, AM can help to increase profits [Chen15]. On the ecological level, the use of AM results in less material waste and enables the lightweighting of parts, which leads to reduced material use [Huan16]. Moreover, the absence of production tools and the reduced logistics associated with AM also imply the greater savings of resources when compared to conventional production scenarios. On the social level, the ability to create customer-oriented products using AM enables greater customer satisfaction, and the openness of AM networks allows for increased national and international interaction on the educational, technological, and cultural dimensions [Chen15]. In addition, conventional manufacturing requires metalworking fluids, which leads to oil mist—a major health

concern for human workers. Since AM does not require metalworking fluids, the risk of oil mist is absent with AM [Huan13].

#### *2.1.5.2 Challenges and obstacles of AM*

While AM offers numerous benefits and has significant potential for wider application in the future, the following challenges and obstacles remain to be overcome:

- **High investment costs**: According to *Wohlers Report 2019*, the average selling price of a metal AM machine was $413,043 in 2018 [Wohl19]. Depending on the maximum build size and power, the selling price of a laser-based AM machine can be over $1 million [Wohl19]. Given the additional costs for auxiliary equipment, staff training, and the recruitment of new employees, the high investment cost is one of the most important obstacles to a wider application of AM [Yi19].
- **Build size and build rate**: Size restrictions and long production times for large-scale products have been obstacles to the rapid adoption of AM [Atta17]. A large-scale part refers to a physical object with a longest axis of at least 1 to 2 m [Nycz16]. Today, the most common build size of powder bed fusion systems is 250 x 250 x300 mm, and the build volume of the largest SLM system is 800 x 400 x 500 mm [Nycz16]. Only a limited number of directed energy deposition systems are capable of processing large-scale metal products [Fraz14]. In addition to build size, the slow build rate is another obstacle. The processing time of an AM system can range from hours to days to even weeks depending on the AM process, part size, parameter sets, and system configurations. Due to these lengthy build times, control over the process is critical, as any failure during the process can void the entire build task, resulting in defective products and waste of time and cost.
- **New materials**: Although the range of products that can be processed by AM systems is increasing, industries still require materials that are suitable for use in AM processes and that exhibit superior performance and unique functionalities. Among these are *digital materials* (or *digital composites*), in which two or more composite substances are combined simultaneously through jetting processes [Pan16]. Depending on the process used, the resulting digital material will have unique electrical, optical, or thermal properties. Another type of material is *shape memory materials*, which exhibit time-dependent shape-changing behavior and can be used for the self-assembly or self-repair of products [Mome17]. The implementation of AM processes for *shape memory materials* is also called 4D printing, since the time-dependent behavior is considered to be the fourth dimension, and 4D printing also implies the next evolutionary stage of 3D printing [Choi15].
- **Reliability and reproducibility**: The mechanical properties of metal parts produced by AM can be comparable to or even superior to those produced using conventional manufacturing processes. However, two open questions remain to be answered: The first is whether this high quality of materials can be reproduced consistently for different products, while the second is whether AM production processes will prove stable and reliable for long production runs [Dowl20, Jahn15]. The quality of products made with AM is determined by numerous factors, such as material, machine, process, system, or even CAD model used. The relevant quality features are surface finish, geometrical accuracy, mechanical properties, and porosity [Schm17].
- **Lack of AM knowledge and tools**: Lack of knowledge concerning AM materials, design methods, software, or other relevant aspects has been a significant barrier to the adoption

of AM by production companies [Yi19]. However, this situation could change in the near future. Today, national and international standardization institutes (e.g., Technical Committee 261 of ISO and Technical Committee 105 of the Association of German Engineers) are working on series of standards for addressing AM-related issues (e.g., standards related to the classification of processes, the testing of materials, and product design). Some of these standards have already been published, while others are under development. These standards are intended to help production companies to gain more knowledge about AM.

- **Intellectual property and patents**: While legitimate producers may use AM to shorten their development and production process, copycats may use AM to facilitate the process of illegally copying the products of original manufacturers. Current legal frameworks for patents and intellectual property protection should be adapted to take into account copyrights, utility patents, design rights, trademarks, and other legal issues related to AM [Bech15].

## 2.2 Environmental properties of AM

### 2.2.1 Potentials and advantages of AM

Due to the increasing global population and higher expectations in terms of quality of life and minimization of resource consumption and environmental impacts, modern production systems are required to be cleaner and more sustainable [Herr10]. Against this background, numerous studies have addressed the quantification, evaluation, and improvement of environmental performance in manufacturing; the resulting tools, methods, approaches, and concepts are referred to using different terminologies, such as “sustainable production,” “green manufacturing,” or “full lifecycle engineering” [Link16, Dorn13, Herr10]. Compared to conventional manufacturing processes, AM processes are considered to be “clean” in that they improve the environmental performance of production processes [Yang19, Lebo14]. The environmental performance of production refers to measurable results related to different environmental aspects, such as energy use, greenhouse gas emissions, or any other impact categories [ISO15a]. Therefore, in terms of improving the environmental performance of manufacturing processes, AM demonstrates the following advantages, which are also referred to as the *environmental benefits of AM*:

- **Lightweighting and functional improvements**: AM enables the use of topology optimization, lattice structures, composite materials, and other lightweighting methods. Lightweighting implies less material usage during the production phase of a product lifecycle, and lightweight products can also prove beneficial for the environment during the use phase. For example, due to lightweighting, Boeing 787 aircraft are 20% lighter than similar aircraft, resulting in a 10–12% fuel efficiency improvement during the use phases of these aircrafts [Mari14]. Moreover, through functional improvements, AM may lead to more environmentally friendly customer behavior and end-of-life management for products [Horn12].
- **No or fewer product-specific tools and fluids**: The absence of dies, cutting tools, fluids, and other product-specific auxiliary materials or systems implies the absence of their production, transportation, storage, maintenance, and disposal. Therefore, the resources

that would be used for them are saved or reduced with AM, and the environmental impacts caused by these tools, materials, and systems are also eliminated or reduced [Morr07].

- **Less material waste**: AM produces fewer scraps than conventional manufacturing. For example, in powder-based AM processes such as SLM or LMD, powders that remain after a build task can be recycled, screened, and reused [Serr11]. In AM processes, scraps are only produced at certain limited points, e.g., the destruction of the support structure or during post-subtractive processing.
- **Reduction of manufacturing processes and shortening of supply chains**: AM enables part consolidation, in which multiple parts are integrated into single complex parts. Therefore, the corresponding manufacturing steps are reduced, and supply chains are shortened. It is estimated that by 2025, the primary energy and $CO_2$ emission intensities of the manufacturing industry could be reduced by a maximum of 5% through supply chain re-organization by means of AM implementation [Gebl14].
- **Circular economy**: By using recycled materials for AM, the lifecycle of a product created by AM can be expressed in a circular fashion, and the scraps created during the production of a product can be recycled and reused in future AM processes [Saue19, Desp17]. In addition, during the use phase, products can be repaired by AM, while, during the end-of-life phase, a product can be remanufactured or reused [Lein16].

### 2.2.2 Debates on the environmental benefits of AM

Despite the various advantages discussed above, recent studies have also claimed that there is a need to more critically examine the environmental benefits of AM. In terms of the improvement of energy performance, AM is associated with the following concerns:

- **Production of feedstock**: Compared to conventional manufacturing, which is not sensitive to the shape of feedstocks, feedstocks for AM processes must be produced in specific shapes [Kell17]. For example, for binder jetting and powder bed fusion processes, metal powers should be produced by for instance water or gas atomization that require a significant amount of energy [Vanl17, Chen15]. For printing metal parts with material extrusion, metal should be produced into powders and then combined with binder matrix into filaments. Subsequently, the production of feedstocks for AM needs extra resources and causes more environmental impacts.
- **Cutting tools and fluid in post-processing**: While cutting tools or fluid are not required during the build phase of AM processes, they are still needed during the post-subtractive processing to improve the quality of AM parts [Vanl17]. Therefore, the tools and auxiliary materials that are claimed to be absent with AM implementation are still not avoidable. Consequently, the resources that should be saved due to their absence are still consumed.
- **Long build times**: The build times of AM processes can range from hours to days depending on the process parameter set and the machines used [Atta17]. Longer build times imply increased electricity consumption and a higher risk of failure. Should an error occur during the process, the build will need to be repeated; as a result, the produced layers will be scraped, and consumed energy will be wasted. Moreover, the handling of failure layers may require additional cost, time, and resources; for example, in SLM, components should be removed from the platform by means of mechanical operations.
- **Dependency on digitalization**: In AM, a build task begins with a digital parameter set, and the process monitoring and control are based on camera-based image collection and

analysis (e.g., [Mazz17]). Therefore, these requirements imply that the application of AM is highly dependent on digital technologies [Bour16]; this is in contrast to subtractive manufacturing, which was used for centuries prior to the invention of computers. It is well known that digital technologies require significant amounts of electricity [Morl18]; the dependency of AM on digital technologies thus also implies greater electricity demands and environmental impacts.

- **Rebound effects**: AM enables better product quality and functionality and decreased manufacturing costs, leading to lower product prices. Therefore, the functional and economic advantages of products created using AM will lead to more buying and consuming of such products, which would then increase the overall resource consumption and environmental impacts of AM [Sorr08].

To ensure the environmental benefits of AM and to overcome the shortcomings that may limit these benefits, the environmental dimension of AM should be regarded more critically and researched further [Baum17a]. Specifically, the following topics are important:

- **Quantitative assessments of AM processes and systems**: The quantification of the environmental impacts is the prerequisite for a deeper understanding of the environmental performance of AM (e.g., in terms of resource consumption, waste management, and pollution control [Peng18]). Among the various environmental dimensions, energy issues merit greater research attention [Reje18]. Recent research has shown that the energy performance of AM can be worse than that of conventional manufacturing in specific cases, and the energy use of AM is sensitive to many impact factors, such as part size, build orientation, batch size, process parameters, and machine configuration [Kell17]. In addition, energy use is related to other economic and ecological issues, such as costs and carbon emissions, and this topic therefore requires further research.
- **Comparison of AM with conventional manufacturing in multiple life phases**: Compared to conventional manufacturing, AM demonstrates both advantages and disadvantages in different life stages. Therefore, the quantification of the environmental impacts of AM and the comparison thereof with those of conventional manufacturing should be performed throughout different life phases (e.g., production phase, distribution of products, and end-of-life) to avoid creating a simplistic picture [Baum17a].
- **Raw materials and feedstock**: Only a few studies have addressed the technical and environmental issues associated with the production of feedstock for AM (e.g., [Falu17, Pari16]). The extraction of raw material and the production of feedstock are important research topics with regard to AM, especially in terms of inventory analysis and assessing environmental impacts [Kell17].
- **Eco-design methods**: Since the environmental impacts of AM may be critical issues, a key question that arises is how these impacts can be minimized and the environmental benefits of AM ensured [Baum17a]. A promising solution is eco-design, in which environmental aspects are considered in the design phase; future work should pay more attention to this issue [Peng18, Baum17a].
- **Sustainable business models and supply chains**: AM enables innovative business models, shortened supply chains, and decentralized production networks, and these adaptions are intuitively perceived as more sustainable [Chen15]. However, recent research has only focused on production networks or supply chains for a single or a small number

of products made using specific AM equipment. Future research should adopt a broader perspective and consider wider AM production networks and multiple life stages of products within such networks [Ford16].

- **Policies, control strategies, and regulations**: AM leads to changes in production and consumption and even in society; hence, new policies, regulations, and legal frameworks are required [Reje18]. From an ecological perspective, research communities and policymakers should focus on the development of new standards and best practices, as well as guidelines for the operation of AM equipment, division of responsibilities, handling of material and waste, pollution control, assessment criteria for environmental impacts, and other environmental issues related to AM [Reje18, Verh18].

It is urged that research communities related to AM address the abovementioned research. Therefore, it should be noted that this dissertation focuses exclusively on eco-design for AM and does not address other issues. The motivation for this decision, as well as the theoretical background of eco-design, is presented in the next section.

### 2.2.3 Energy performance of AM

Compared to environmental performance, in which different impact categories are considered, energy performance focuses exclusively on measures related to the energy consumption, energy efficiency, and energy use of a system or process and omits all other impacts [ISO15a]. Energy performance is one of the most important environmental issues associated with AM due to the following reasons:

- **Energy is a key factor causing the environmental impacts of AM**: In AM, high-power devices such as laser transmitters are widely used [Lee17]. Therefore, electricity consumption during build processes is significant. According to a study conducted by FALUDI ET AL., in the cradle-to-gate impact of SLM, electricity consumption accounts for a share of approximately 80% of the embodied energy, and the proportion of the impact caused by electricity consumption ranges from approximately 67% to 75% of the total cradle-to-gate impact [Falu17]. Compared to electricity consumption, the impact caused by material waste, argon, and machine transportation and disposal is negligible, and the impact caused by powder production never accounts for more than 10–12% of the total impact [Falu17]. The fact that energy use accounts for the majority of the environmental impacts of AM implies that the improvement of the energy performance of AM is a key factor in improving the environmental performance of this process.
- **Energy performance is sensitive to many factors in AM**: The energy performance of AM can be influenced by many factors. Product-related factors include the materials used, part size, and number of parts featured in a build task [Kell17]. Generally, melting metal parts requires more energy than melting plastic parts, and larger parts require more build time and electricity use than small parts. Process-related factors include build orientation, build speed, layer thickness, and scan pattern [Yi20a]. Changing the build orientation leads to changes in the support structure and number of layers, which in turn result in different levels of energy consumption. For the same reason, should changes be made to the build speed, layer thickness, and/or scan pattern, the build time and energy use will be impacted as well. In addition to product- and process-related factors, factors related to machines and

technologies can also influence the energy use of AM (e.g., a ytterbium fiber laser transmitter is more efficient than a carbon dioxide laser transmitter [Lee17]).

- **Lower energy efficiency and high specific consumption**: In laser-based AM processes, the heat radiation, reflection, conduction, and convection of molten pools lead to high energy waste. For example, the adiabatic efficiency of laser AM processes (the ratio between the actual build rate with heat loss and the theoretical maximum build rate without heat loss) varies from 3.6% to 7% for aluminum and from 9% to 23% for steel [Guto17]. The specific energy consumption (energy consumption per 1 kg material) of AM processes can be one to two orders of magnitude higher than that of machining and molding processes [Kell17].

In summary, the energy performance of AM processes is not always superior to that of conventional manufacturing processes and deserves more research attention. As described in the next subsection, to ensure the environmental benefits and to improve the energy performance of AM, eco-design approaches are needed in the AM design phase.

## 2.3 Eco-design and its implication for AM

### 2.3.1 General eco-design and its definition and concepts

#### *2.3.1.1 Origins and definition of general eco-design*

The origins of the term "eco-design" can be traced back to the 1980s, when it was proven that end-of-pipe technologies were unable to deal with growing environmental problems such as resource shortages and heavy industrial pollution [Hübn12]. End-of-pipe technologies address emissions and pollutions at the end of production activities without making any changes to the processes involved in those activities [Yari03]. Since pollution and wastes are already generated, the treatment thereof requires additional equipment and investment. For reasons of cost and efficiency, at the end of the 1980s, industry adopted a more preventive approach called "middle-of-pipe" or "cleaner production," in which waste and resource consumption are minimized by modifying production processes in a cleaner fashion [Math07]. At the same time, another concept, namely eco-design, was introduced, in which the focus of the treatment of environmental issues is further emphasized in the design phase of a product lifecycle [Karl06].

The main motivation for considering environmental impacts in the product design phase is due to the following two factors: First, the initial product idea and design concept have a great influence on the ultimate life phases and the corresponding environmental impact of that product [McAl15]. As depicted in Figure 2-17A, approximately 80% of the fixed environmental impacts in a product lifecycle can be influenced in the early concept phase [Tisc00]. Second, as shown in Figure 2-17B, over the entire lifecycle of a product, the costs of reducing environmental impacts trend to increase, while the opportunities to reduce environmental impacts tend to decrease. This is because once products are manufactured and distributed to the market, changes to the designs of those products will require modifications to the underlying supply chain or distribution network or even the recall of sold products, resulting in additional costs and environmental impacts [Yi20b]. Therefore, the design phase encompasses the most opportunities to reduce environmental impacts at lower costs, and production companies should thus engage in eco-design.

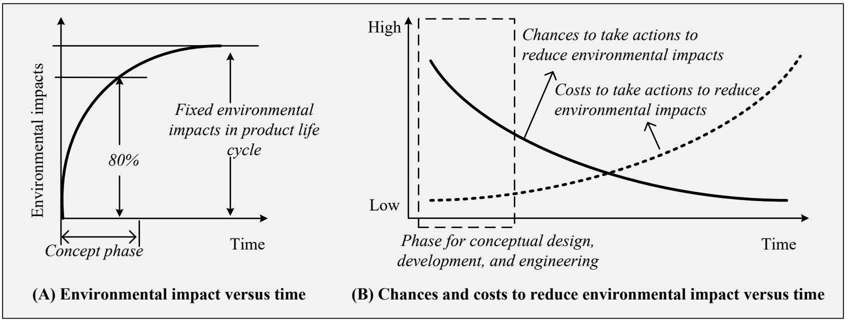



Figure 2-17: Motivations for engaging in eco-design (adapted from [Yi20b])

In the literature, different definitions of the term "eco-design" exist; these can be distinguished on the basis of whether they adopt a *product-* or *general solution-based* perspective:

- **Product-based perspective**: From a product-based perspective, the term "design" specifically refers to *product design and development*. The overall objective is to minimize resource consumption and the consequent environmental impact and to maximize customer benefits during the product design stage [Char10]. Examples of definitions that adopt a product-based perspective are those proposed by ISO 14006 and CHARTER AND TISCHNER. According to ISO 14006, eco-design is defined as the "(..) integration of environmental aspects into product design and development, with the aim of reducing adverse environmental impacts throughout a product's life cycle (…)," in which product can be "(..) any goods or service (…)" [ISO11]. CHARTER AND TISCHNER define eco-design as "(..) strategies that aim to integrate environmental considerations into product design and development (…)" [Char10].
- **General solution-based perspective**: From a general solution-based perspective, authors who have offered a definition of eco-design from a general solution-based perspective do not specifically state that the term "design" should be understood as meaning "product design and development". Hence, the design object can be not only products but also systems, organizations, or any other factors related to environmental issues [Hübn12]. Examples of definitions that adopt a general solution-based perspective are those proposed by VAN DER RYN AND COWAN and KARLSSON AND LUTTROPP. VAN DER RYN AND COWAN define eco-design as "(..) any form of design that minimizes environmentally destructive impacts by integrating itself with living processes (…)," while KARLSSON AND LUTTROPP define eco-design as "(..) a concept that integrates multiple aspects of design and environmental considerations (…)" [Van07, Karl06].

In the context of eco-design for AM, the general solution-based perspective may be more appropriate because the environmental impacts related to AM can be influenced and reduced by different design aspects, including not only product design but also the design of process parameters, production network design, the design of AM equipment, and other relevant design issues. Therefore, in line with the general solution-based perspective, this dissertation defines eco-design for AM as "*any type of design in which AM and environmental issues are considered*".

In addition, it is important to note that eco-design is not the same thing as *sustainable design*. While sustainable design covers ecological, economic, and social dimensions, eco-design only focuses on the ecological dimension [Char10]. Therefore, this dissertation only focuses on the environmental issues associated with AM and does not consider social and economic issues.

#### *2.3.1.2 Legal eco-design framework in Europe*

The first EU directive on eco-design was *Directive 2005/32/EC*, which focused on the improvement of the efficiency of energy-using products because they account for a large proportion of the consumption of natural resources and energy [Euro05]. *Directive 2005/32/EC* was proposed to amend three previous directives: *Directive 92/42/EEC* on efficiency requirements for hot water boilers; *Directives 96/57/EC* on efficiency requirements for household electric cooling devices; and *Directive 2000/55/EC* on efficiency requirements for ballasts for fluorescent lighting. These directives are depicted in Figure 2-18 [Euro00c, Euro96, Euro92]. The focus of *Directive 2005/32/EC* was mainly on energy issues and the improvement of energy efficiencies, and its creation was related to other EU activities, such as the *European Climate Change Program* (ECCP) [Euro00a].

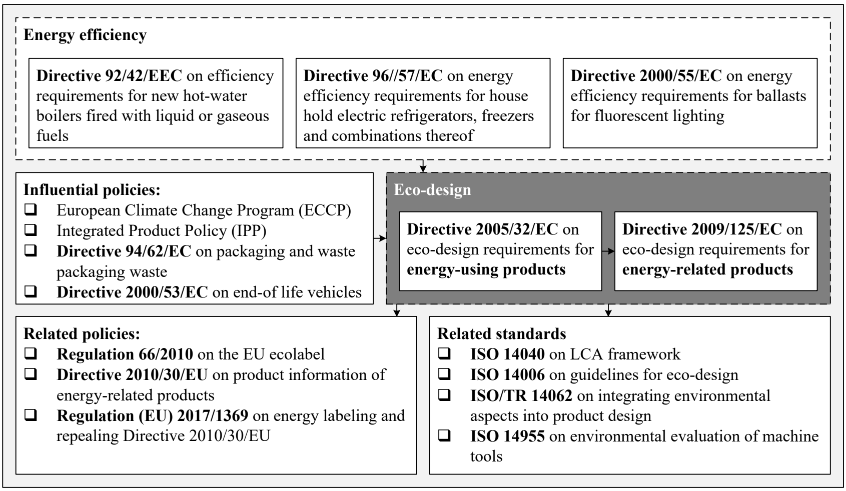



Figure 2-18: Legal framework for eco-design in Europe (adapted from [Sany14])

In 2009, *Directive 2005/32/EC* was replaced by *Directive 2009/125/EC*, in which the focus on eco-design has been extended from energy efficiency to include the assessment of the environmental impacts of entire product lifecycles [Sany14]. This modification was mainly driven by an increasing concern regarding the environmental impacts of products and services and lifecycle thinking, especially since the *Integrated Product Policy* (IPP) came into force [Sany14, Euro01]. Moreover, other policies, such as *Directive 94/62/EC* on packaging and packaging waste and *Directive 2000/53/EC* on end-of-life vehicles, positively influenced the eco-design framework [Sany14, Euro00b, Euro94].

After *Directive 2009/125/EC* was published, it had a positive impact on other policies, such as *Regulation 66/2010* on the EU ecolabel and *Directive 2010/30/EU* on the indication by labeling the standard product information of the energy or other resource consumption, which was later replaced by *Regulation 2017/1369* [Euro17, Euro10b, Euro10a]. From an eco-design tools perspective, the ISO has published various standards addressing the basic methodologies used in assessing and reducing environmental impacts in production activities. Examples are *ISO/TR 14062* and *ISO 14006* on guidelines and general frameworks for eco-design in product design and development, *ISO 14040* on the LCA framework, and *ISO 14955* on the environmental evaluation of machine tools; these standards are depicted in Figure 2-18 [ISO18, ISO17, ISO11, ISO06, ISO02].

### *2.3.1.3 Levels of eco-design*

In general, trends, challenges, and other issues related to eco-design can be discussed on the following four levels: the system success level, the strategy level, the action level, and the tools level. These levels are shown in Figure 2-19 and described in the following [Paul15].

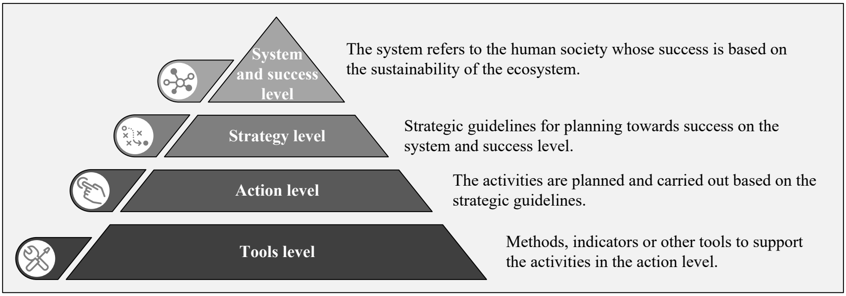



Figure 2-19: Four levels of eco-design (based on [Paul15])

- **System and success level**: The term “system” refers to human society acting within the ecosystem. The term "success" implies that nature is not faced with increased material extraction from the earth, overwhelmed by production activities, or degraded by physical means in the course of meeting human needs [Robè02].
- **Strategy level**: To achieve success throughout human society, general strategies and guidelines should be specified. When maintaining the ecosystem, economic benefits should also be considered to avoid a lack of economic resources.
- **Action level**: The plans, guidelines, and policies identified at the strategic level should be further refined on the operational dimension, where activities related to eco-design are planned and implemented to ensure that strategies are successful.
- **Tools level**: This level describes the measures, methodologies, software and hardware, and other tools used to support the activities at the action level.

In the context of this dissertation, the discussion is limited to the action and tools levels, as the aim is the development and validation of a methodological framework containing design and assessment activities and tools intended to facilitate eco-design by AM users.

## 2.3.2 Eco-design for AM and its benefits and challenges

### *2.3.2.1 Concept of eco-design for AM*

The concept of eco-design for AM can be regarded as involving interactions among three fundamental domains: *manufacturing*, *product lifecycle*, and *sustainability* (see Figure 2-20). The *product lifecycle* domain comprises four core stages: *design*, in which product idea, a rough concept, and detailed engineering solutions are defined and validated; *production*, in which the components are manufactured and assembled into products; *use*, in which products are implemented for specific purposes; and end-of-life, in which products that have exceeded their lifespans are recycled and disposed [West00]. As described in Section 2.1.1.3, the *manufacturing* domain encompasses *additive*, *subtractive*, and *formative* manufacturing as three essential elements [ISO15b]. The *sustainability* domain consists of three fundamental dimensions: *ecology*, in which interactions between humans or other life forms within the surrounding environment enable sustainable development; *economy*, in which the production, distribution, and consumption of goods or services are realized in a sustainable form; and *society*, in which systems of individuals with same cultural characters are required to achieve a sustainable existence [Unit05]. By combining *design*, *ecology*, and *AM* from the respective domains, the new domain of *eco-design for AM* arises.

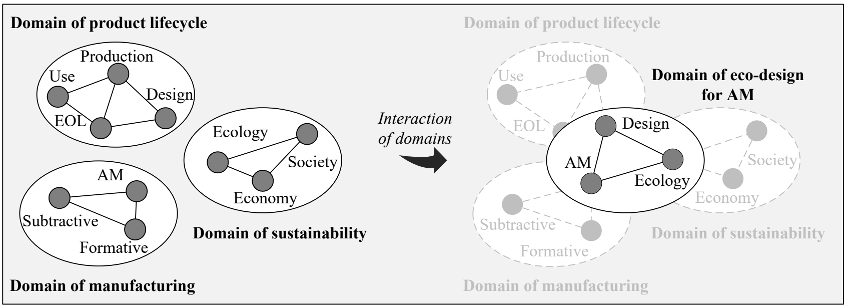



Figure 2-20: Rise of the concept of eco-design for AM

Based on the concept that eco-design arises from the domain interaction, an eco-design for AM approach should exhibit the following properties:

- ❑ **Use of innovative design tools to improve the environmental performance of AM**: This property refers to the use of innovative design techniques that are appropriate for AM to propose design solutions that are more environmentally friendly. In accordance with the general solution-based perspective introduced in Section 2.3.1.1, the design object can be a product, supply chain, production network, business model, or other design object related to AM.
- ❑ **Evaluation of the environmental performance of AM**: This property refers to the use of quantitative or qualitative evaluation methods (e.g., LCA or energy performance assessment) to analyze the environmental performance of AM-specific design solutions (e.g., emissions, material and energy use, resource depletion, or other environmental impacts).

- ❑ **Consideration of specific features of AM processes**: This property describes the use of AM processes and consideration of their functions, cost, materials, system characters, or other technological features during design and evaluation activities.

#### *2.3.2.2 Design and evaluation tools in eco-design for AM*

In general, each eco-design for AM approach should comprise at least two tools: *a tool for environmental evaluation* and *a tool for environmental design* [Dieg16, LePo07]. While the *evaluation tool* aims at identifying and quantifying the scale of the environmental impacts caused by AM, the *design tool* describes the formulation of the parameters of design solutions with AM. The following two tools are widely applied for the environmental evaluation of AM:

- ❑ **LCA**: Generally, LCA should be performed in four phases: *goal and scope definition*, in which the functional unit, system boundaries, impact categories, and other general requirements are specified; *inventory analysis*, in which the inventory flows into (e.g., electricity use, water use, and land use) and out of (e.g., heat, emissions, and waste) the system boundary along the product lifecycle are quantified; *lifecycle impact assessment* (LCIA), in which the environmental impacts of AM are quantified in different equivalent indicators (e.g., $CO_2$-eq. in kg) based on inventory data; and *interpretation*, in which significant issues are addressed and recommendations are made. During the LCIA, different methodologies can be used, in which the impact categories and calculation methods of the equivalent indicators may differ. For example, cumulative energy demand (CED) only considers the impact categories of primary energy carriers (e.g., fossil, solar, and wind power), while ReCiPe covers the impact categories such as climate change, acidification, and human toxicity. By using LCA as well as different LCIA methodologies, the environmental impacts of AM can be assessed in terms of different focal impact categories.
- ❑ **Energy-related metrics**: Compared to LCA, energy-related metrics and evaluation methodologies omit other impact categories and only focus on energy issues. On the machine level, the most widely used energy metrics are, for instance, total energy consumption in J or kWh, specific energy consumption in MJ/kg, or exergy efficiency in %. On the process chain level, the most used energy metric is primary energy. By using these energy-related metrics, the energy performance of design solutions with AM can be quantified and assessed.

The following three types of tools for environmental design in eco-design for AM can be found in the existing literature:

- ❑ **Product-related design tools**: On the product level, common environmental design tools include topology optimization, use of porous structure, part consolidation, and multi-material design. In topology optimization, finite element analysis (FEA) is used to evaluate the performance (e.g., in terms of stress and strain) of a product under certain mechanical conditions, and the geometrical layout of the product is meshed based on given optimization objectives (e.g., reduction of weight). Porous structures such as lattice and honeycomb structures are suitable for AM, as they can simultaneously improve the functionality and reduce the weight of a product. In part consolidation, multiple components within an assembly are integrated into one or few components with greater complexity, which leads to the reduction of the manufacturing steps involved and the saving of resources. Multiple material design enables the combination of different materials in one component to simultaneously improve its functionality and make it more environmentally friendly. In summary, product-related design tools are used to endow products with certain geometrical or material properties.

- **Process-related design tools**: These design tools refer to different methodologies for process or process chain planning. Process planning aims to determine process parameters such as build rate, layer thickness, and laser power while taking into consideration environmental performance, product quality, and process performance. In process chain planning, the design focus lies on determining the logical sequence of AM process and peripheral processes such as build task preparation and post-processing, taking into consideration both the environmental performance of the process chain as well as its productivity and manufacturability.
- **Business model-related design tools**: On the business model level, the design focus is on issues related to value creation and transfer of AM products between production networks and customers. During the design process, both environmental performance and business opportunities should be considered.

#### *2.3.2.3 Benefits and challenges of eco-design for AM*

As described previously, eco-design for AM is key in investigating, assessing, and ensuring the environmental benefits of AM [Peng18, Baum17a]. On the level of production companies, the implementation of eco-design for AM offers the following benefits:

- **Confirmation of the environmental benefits of AM**: Using quantitative assessment tools such as LCA enables the comparison of the respective environmental impacts of AM and conventional manufacturing [Dieg16]. Therefore, eco-design for AM enables the investigation and confirmation of the environmental benefits of AM.
- **Reduction of environmental impacts with AM**: Considering environmental issues in the design phase with AM enables decreasing resource consumption and environmental impacts during the production, use, and end-of-life phases with AM [Yang19, Huan16].
- **Stimulation of creativity in product and business model innovation**: Using innovative design tools allows for greater creativity in designing products, processes, production and service networks, supply chains, distribution channels, and business models with AM [Ohar15].
- **Increased competitiveness and reduction of costs**: In line with the reduction of material and energy consumption, the costs associated with energy use and waste management can also be reduced [Thom16a]. The reduced costs and the enhanced product or business opportunities associated with AM can further strengthen the core competitiveness of companies [ISO11].
- **Better compliance with relevant regulations and improved public images**: Using eco-design for AM can help companies to comply with current regulations or the more restrictive normative conditions that are anticipated in the future [Sany14]. Moreover, the reduction of environmental impacts also implies the creation of better public images for companies in terms of taking responsibility for global sustainable development [Ohar15, ISO11].

However, the implementation of eco-design for AM is also faced with the following challenges that need to be overcome:

- **Determining design scope with AM**: The design objects of eco-design for AM can be products, processes, production networks, life phases, or other design issues related to AM. Therefore, the definition of an appropriate design scope needs to be considered at the beginning of eco-design for AM.
- **Collaboration between design and assessment activities**: Design and assessment activities should not be isolated from each other, as eco-design for AM represents a holistic framework for ensuring the environmental benefits of AM. Therefore, the integration of different activities within an eco-design for AM framework may prove challenging and should be appropriately arranged before they are carried out.
- **Quantification of the environmental profiles in the early phase**: The quantification of environmental performance requires inventory data of AM processes and systems. However, in the design phase, processes may not have been implemented, and the relevant systems may not have been purchased; therefore, it would be impossible to conduct experiments for data acquisition. Consequently, the inconvenience of data collection in the early phase may challenge eco-design for AM in terms of the quantification of the environmental performance of AM.
- **Methods and criteria for assessment and decision-making**: A design case with AM is subject to the internal or external design requirements proposed by companies or customers. Thus, determining which methods or criteria should be considered can be a challenge during design and assessment activities.

### 2.3.3 Requirements for general eco-design for AM approaches

Based on the concept and properties of eco-design for AM, the following requirements are identified as the boundary conditions that general eco-design for AM approaches should fulfill; these requirements are also considered in developing the framework in this dissertation.

**Requirement 1: Description of the environmental performance of AM**

The description of the environmental performance of AM is the prerequisite for quantifying and improving that performance. The environmental performance of AM refers to measurable results related to different environmental aspects, such as energy use, greenhouse gas emissions, water consumption, or any other environmental impact related to AM [ISO15a]. In eco-design for AM, environmental performance should be described in metrics that represent the condition or status of AM processes in terms of environmental properties. More specifically, the term "description" refers to, first, choosing at least one impact category of environmental performance, and, second, using at least one metric to quantify the selected impact category.

**Requirement 2: Enabling convenient and reliable energy predictions of AM processes**

The quantification and improvement of the environmental performance of AM require accurate prediction of the material and energy use of AM processes. The material use can be defined as the sum of the volumes of a component and its corresponding support structure. However, the energy use of AM is difficult to quantify because it can be influenced by many factors, such as machine configuration, part design, and process parameters. In the design phase, experiments are not suitable because AM build times can be up to hours or days, and time-intensive experiments will significantly increase the overall design cost and time. Thus, rapid and reliable energy predictions are required for eco-design for AM approaches.

**Requirement 3: Integration of assessment and design activities**

Since eco-design for AM represents a holistic framework for identifying, evaluating, and ensuring the environmental benefits of AM, the related assessment and design issues should be integrated. The assessment activity aims at quantifying the energy performance of a design solution with AM, whereas the design activity seeks to improve the energy performance of this solution with respect to the assessment results.

**Requirement 4: Integrated consideration of design benefits and environmental impacts**

Eco-design for AM aims at the maximization of the design benefits of AM while minimizing environmental impacts. The design benefits of AM include, but are not limited to, improved functionality, increased customer satisfaction, cost benefits, enhanced manufacturability, and other benefits related to the use of AM. Therefore, in eco-design for AM, the design benefits and environmental impacts of AM should be considered and evaluated in an integrated fashion.

**Requirement 5: Convenience, ease-of-use, and robustness**

Different designers have individual design needs. An eco-design for AM approach should be robust enough to solve a variety of different design problems, not just one specific problem. In addition, good design and evaluation tools can significantly reduce development costs and time. Therefore, convenient usability, modifiability, and robustness are required for an eco-design for AM approach.

## 2.4 Existing approaches related to eco-design for AM

Based on the requirements defined in Chapter 2.3.3, existing approaches related to eco-design for AM are collected, specified, and analyzed. Whether an approach is included in this chapter depends on whether it meets at least one of the five requirements identified previously. In assessing the existing approaches, it can be concluded that they can be clustered into the following five categories.

### 2.4.1 Category I: Unit process inventory and impact analysis

Studies that fall in this category feature experiments intended to measure electricity use for specific AM machines. By applying analytical models and LCIA methods, inventory data (i.e., concerning material and electricity consumption) can be converted into equivalent environmental impact indicators (e.g., midpoint indicators such as $CO_2$ emission and endpoint indicators such as damage to human health). The relevant studies are described below:

- ❑ BALOGUN ET AL. carried out experiments on the *Stratasys Dimension SST FDM* system and calculated its $CO_2$ emissions using analytical models [Balo15]. The authors concluded that the increased part volume and complexity lead to higher electricity consumption and a greater carbon footprint. Moreover, BALOGUN ET AL. also found that post-processing accounts for a significant portion of the total energy consumption and carbon footprint.
- ❑ BAUMERS ET AL. performed experiments to analyze the electricity consumption of six AM systems: the *SLM250*, the *M3 Linear*, the *EOSINT M270*, the *A1*, the *EOSINT P390*, and the *FDM 400mc* [Baum11]. In this study, it was observed that the capacity utilization of a

build task has an impact on the specific energy consumptions of AM machines, especially for SLS/SLM and EBM.

- BAUMERS ET AL. measured and modeled the electricity consumption and build costs of an *EOSINT M270* machine using a series of experiments [Baum13]. The proposed cost and electricity consumption models enable the rapid and reliable estimation of the cost and energy consumption of the studied AM machine.
- KELLENS ET AL. performed experiments on four AM machines: the *EOSINST P760*, the *EOSINT P360*, the *EOSINT FORMIGA P100*, and the *Concept Laser M3 Linear* [Kell11]. The authors quantified and analyzed the electricity, compressed air, and powder consumption of these machines; their results represent valuable inventory data for SLS and SLM processes.
- LUNETTO ET AL. measured the electricity consumption of the *Arcam A2x* EBM machine and modeled the electricity consumption based on the average deposition rate of the process [Lune20]. The results show that the specific energy consumption of EBM demonstrates a hyperbolic correlation to the average deposition rate.
- NAGARAJAN ET AL. carried out experiments involving the *Fast Mask Image Project Stereolithography* (MIP-SL) process and evaluated the environmental impacts of producing six components using the ReCiPe LCIA method [Naga17]. The authors modeled energy consumption with the build time using empirical methods, and the resulting model can be used for energy predictions.
- SREENIVASAN AND BOURELL measured and analyzed the energy consumption of the *Vanguard HiQ+HS* SLS machine [Sree09]. The authors concluded that the chamber heater subsystem of the machine consumed the most energy, followed by the stepper motors, roller, and laser device.
- WATSON AND TAMINGER applied parametric modeling to the energy consumption of general AM processes [Wats18]. In their model, the energy consumption of AM. including the feedstock production, transport, removal of supports, and post-processing, is expressed as a function about part volumes and other assumed variables.
- WIPPERMANN ET AL. performed experiments on three AM systems, the *Trumpf TruPrint 1000*, the *EWM alpha Q352*, and the *DMG Mori Lasertec 65 3D*, and compared the electricity use of these devices with that of a milling machine [Wipp20]. The authors concluded that the implementation of a hybrid additive-subtractive manufacturing strategy at higher material removal ratios will reduce the electricity demand of the process.
- XU ET AL. measured and modeled the electricity consumption of a binder jetting machine using a physical parametric approach [Xu15]. The outcome of this study is a validated model for the prediction of the energy consumption of the studied binder jetting machine.
- YI et al. performed physical modeling and experiments on two AM systems: the *Ultimaker 3* and the *Concept Laser Mlab* [Yi20c, Yi20d]. In their study, a simulation tool was developed and validated to enable the prediction of the energy consumption of the studied AM machines.

### 2.4.2 Category II: Investigation of the influencing factors

The studies that fall into this category involve experiments with various parameters intended to observe the relationship between the selected influencing parameters (e.g., layer thickness and processing speed) and the material and energy use or environmental impacts of given AM machines. The relevant studies are as follows:

- Baumers et al. analyzed the correlation between the process energy consumption of the *Arcam A1* EBM machine and the geometrical complexity of products [Baum17b]. The authors concluded that the process energy consumption of the studied machine shows only weak correlation to the complexity of the shapes of the products.
- Faludi et al. investigated sensitive factors associated with the environmental impacts of the use of the *Renishaw AM250* SLM machine based on the *ReCiPe* Endpoint H/A LCIA method [Falu17]. The authors found that the main environmental impacts of *Renishaw AM250* were caused by the electricity consumption of the machine.
- Griffiths et al. performed two-level full factorial design of experiments (DoE) on four factors: slice orientation, infill, number of shells, and layer height [Grif16]. In their experiments, they studied the *Makerbot Replicator* FDM machine and examined the part weight, scrap weight, and energy consumption. The results showed that the slice orientation has a great impact on scrap weight, that the infill and number of shells are factors in determining part weight, and that the layer height is most sensitive to energy use.
- Kellens et al. studied the energy consumption and environmental impacts of the *EOSINT P760* SLS machine using the *ReCiPe* Endpoint LCIA method [Kell14]. The authors found the influencing factors to be the layer thickness, nesting efficiency, process chamber, and machine control.
- Luo et al. compared the environmental impacts of different SLA, SLS, and FDM machines based on the Eco-indicator 95 LCIA method [Luo99]. The authors concluded that the materials used, energy, and disposal strategies are three important factors in determining the environmental performance of AM.
- Mognol et al. studied the energy consumption of three AM systems: the *Stratasys FDM3000*, the *3DS Thermojet*, and the *EOSINT M250 Xtended* [Mogn06]. The authors identified the heights of parts as the influencing factor for the energy consumption minimization of the *Thermojet* and *EOSINT M250* systems and the volume of supports as the main impact factor for the *Stratasys FDM3000*.
- Song and Telenko studied the material waste and energy consumption of the *Afinia H480* FDM printer [Song17]. The authors found that print failures caused by calibration problems resulted in the most material waste. To reduce energy consumption, the standby and pre-heating times should be reduced.
- Yang et al. performed two-level full factorial DoE on four influencing factors: layer thickness, the curing time for stable layers, curing time transition rate, and orientation [Yang17]. The result showed that the layer thickness has the most significant influence on the energy consumption of a studied machine. Moreover, the statistical model used for the experiments can be used to predict the energy consumption of the machine.

### 2.4.3 Category III: Comparison of AM with conventional manufacturing

Studies falling into this category compare the cradle-to-gate or full lifecycle environmental impacts of AM with those of conventional subtractive or formative manufacturing. For inventory analysis, a number of studies performed experiments to measure the electricity consumption of selected AM machines, while other studies applied empirical inventory data from of previous works or commercial databases. These studies are as follows:

- FALUDI ET AL. compared the lifecycle environmental impacts (using the *ReCiPe* method) of two AM machines, namely the *Dimension 1200BST* and the *Objet Connex 350*, with those of the *Haas VF0 CNC* milling machine [Falu15]. The authors concluded that electricity consumption is the dominant factor in terms of the environmental impacts of AM, while the dominant factor for milling is material waste.
- HUANG ET AL. analyzed and compared the cradle-to-gate primary energy demands and $CO_2$ emissions in different scenarios concerning the production of aircraft components by AM and conventional manufacturing [Huan16]. The authors found that the energy and emission savings of AM may be due to the reduced material requirements for production in AM and the reduction of fuel consumption in the use phase due to the lightweighting of components.
- KREIGER AND PEARCE measured the electricity use of the *RepRep* FDM printer and quantified its cumulative energy demand (CED) and greenhouse gas (GHG) emissions [Krei13]. In their study, they compared the CED and GHG emissions of distributed production scenarios enabled by FDM with those of conventional scenarios. The results confirmed the potential to reduce CED and GHG emissions in the scenarios involving FDM.
- VAN LE ET AL. compared the cradle-to-gate environmental impacts of the *Arcam A1* EBM machine with those of the conventional machining process [Vanl17]. The authors concluded that EBM has less environmental impacts than conventional manufacturing for larger material removal volumes, while, for smaller material removal volumes, conventional manufacturing has less environmental impacts than EBM.
- MORROW ET AL. compared the cradle-to-gate energy and emissions of the laser metal deposition process and the conventional milling process [Morr07]. The results of this study indicated that the production of parts with lower solid-to-cavity ratios with laser metal deposition produces less environmental impacts. Moreover, the remanufacture and repair of tools by AM is an important factor for reducing the environmental impacts of manufacturing.
- PARIS ET AL. compared the cradle-to-gate impact of the *Arcam* EBM machine with that of conventional milling process using two LCIA methods, *CML 2 Baseline 2000* and *CExD* [Pari16]. The result indicated that the EBM process was more environmentally friendly than milling for producing parts that require heavy material removal.
- PRIARONE ET AL. examined and compared the cradle-to-gate and disposal energy consumption and carbon emissions of EBM process with those of subtractive manufacturing, including milling and turning [Pria17b]. The authors found that AM involves lower energy consumption and produces fewer emission when the use of subtractive manufacturing requires more material to be machined off.
- TELENKO AND SEEPERSAD compared the lifecycle inventories of SLS and injection molding [Tele12]. This study confirmed that the energy consumption per part of AM is lower than that of injection molding for small production quantities. Moreover, increasing the number of parts in one build task can significantly reduce the per part energy consumption of AM.
- WILSON ET AL. compared the *Optomec LENS 750* laser metal deposition machine with the conventional casting process in terms of the remanufacturing of a turbine blade [Wils14]. This study compared the energy consumption and $CO_2$ emissions for repairing a defective turbine blade and producing a new blade using casting. The result showed that for small

defects, it would be more environmentally friendly to repair and remanufacture using laser metal deposition than casting.

### 2.4.4 Category IV: Sustainable business models and circular economy

Studies falling into this category focused on the exploration and realization of the sustainable values of AM in terms of business model innovation and new circular economy patterns. These studies are as follows:

- DESPEISSE ET AL. proposed a methodological framework to explore and ensure the sustainable values of AM technologies; this framework applies a road-mapping approach and sustainable value analysis [Desp17]. In their approach, six strategies for ensuring the sustainable values of AM are identified: designing of products and processes for efficiency, manufacturing system configuration, business model, efficiency in use, product life extension, and closing the loop.
- FORD AND DESPEISSE analyzed the potential of AM in terms of sustainability enhancement in manufacturing [Ford16]. This study proposed four categories that enable the sustainability benefits of AM: product and process redesign, material input processing, make-to-order component and product manufacturing, and closing the loop.
- SAUERWEIN ET AL. investigated opportunities in terms of using AM to enable a circular economy [Saue19]. This work identified five circular design strategies: product attachment, durability and reliability, repair and upgrades, dis- and reassembly, and designing for recyclability.

### 2.4.5 Category V: Sustainable design and eco-design frameworks

Studies falling into this category focused on the development of tools or methodological frameworks of eco-design for AM. These studies are as follows:

- LANTADA ET AL. proposed a framework based on the eco-efficient design of support structures [Lant17]. This approach employs a tree-like support structure for AM to reduce the material and energy consumption, cost, and $CO_2$ emissions of AM.
- MA ET AL. developed a framework based a heuristic approach to minimize the material cost and energy consumption of SLS [Ma18]. In this framework, the material cost and energy consumption were modeled as mathematical functions based on process parameters such as layer thickness and laser speed. Using the NSGA-II genetic algorithm, the optimal parameter combination (i.e., that wish the lowest energy use and material cost) can be identified.
- MAMI ET AL. proposed a framework in which the normalized lifecycle costs and environmental impacts of AM and conventional manufacturing scenarios were visualized and compared [Mami17]. Based on the eco-efficiency of each design solution, the authors identified the solution with the lowest costs and environmental impacts.
- MARKOU ET AL. proposed a conceptual framework for eco-design for AM in which four tools are used: the lifecycle design strategies wheel, AM process information sheets, materials cards, and a strengths-weaknesses-opportunities-threats (SWOT) analysis [Mark17]. This approach enables the generation, evaluation, and selection of different product ideas in the early design phase.

- PRIARONE AND INGARAO developed an AM process selection tool in which primary energy demands and $CO_2$ emissions are used to compare different AM processes in the design phase [Pria17a].
- TANG ET AL. proposed a framework in which topology optimization is applied as the design tool and LCA is used as the evaluation tool [Tang16b]. The proposed framework is able to assess and reduce the environmental impacts of product and process design with AM.
- YANG ET AL. developed a framework in which part consolidation and LCA are combined to enable eco-design for AM [Yang19]. Moreover, this study summarized a generic process model for other AM users to execute eco-design for AM.

## 2.5 Assessment of existing approaches related to eco-design for AM

In this chapter, the approaches presented in Chapter 2.4 are evaluated based on the requirements defined in Chapter 2.3.3. The evaluations are presented below.

**Assessment of requirement 1: Description of the environmental performance of AM**

The first requirement is fulfilled by most approaches, as they express the environmental performance of AM in one of two ways. The first way is to use LCIA methods, in which environmental performance is expressed in equivalent environmental impact indicators (e.g., $CO_2$ equivalent for global warming effects and CED for primary resource depletion). Examples are the approaches of KELLENS ET AL., LUO ET AL., and LE ET AL., in which the LCIA methods *ReCiPe*, *Eco-indicator 95*, *CExD*, and *CML* are applied [Vanl17, Kell11, Luo99]. The second way is to focus on energy performance (e.g., electricity consumption or efficiency). Examples are the approaches of YI ET AL., LUNETTO ET AL., and WATSON AND TAMINGER [Lune20, Yi20c, Yi20d, Wats18]. These approaches confirm the understanding that the evaluation and improvement of energy performance can be equivalent to the evaluation and improvement of environmental performance under specific conditions, as it has been proven that electricity consumption is the dominant factor in terms of causing the environmental impacts of AM, and energy issues associated with AM thus merit more research attention [Baum11].

**Assessment of requirement 2: Enabling convenient and reliable energy predictions of AM**

In a handful of approaches, predictions of the energy use of AM are made by either an empirical or a physical method. The empirical method follows a *black box* principle in which the interior of a system is not analyzed. In empirical models, the energy consumption or specific energy consumption of AM is described using hypothetical variables and parameters that are observed from outside of an AM system (e.g., shape complexity or build rate). Examples include the approach of LUNETTO ET AL., in which the specific energy consumption and mean build rate are modeled using a hyperbolic model, and that of YANG ET AL., in which the energy consumption is modeled to parameters in a statistic model [Lune20, Yang17]. In contrast, the physical method employs a *white box* principle that requires the analysis of the interior of a system. A physical model describes the energy consumption of AM using variables that are observed from within an AM system. Examples are the approaches of XU ET AL. and YI ET AL., in which the energy consumption of AM is modeled based on power and time variables [Yi20c, Xu15].

**Assessment of requirement 3: Integration of assessment and design activities**

In a few approaches, design and assessment activities are integrated in one of two ways. The first way is called the "evaluate after design" principle, in which the assessment is executed after the design process or only integrated into the later design stage. Examples are the approaches by TANG ET AL. and YANG ET AL., in which products are first optimized and their entire process chains are defined, after which environmental impacts are evaluated using LCA. The second way is called the "evaluate during design" principle, in which the assessment is integrated into the middle stage of the design process. An example is the approach of MA ET AL., in which the process design is formulated as a multi-objective optimization problem regarding material cost and energy consumption [Ma18]. Since energy consumption is a part of the optimization objective, the search for the optimal process parameters and the evaluation of the energy consumption are carried out simultaneously using a genetic algorithm.

In the "evaluate after design" approach, the collaboration between the assessment and design is relatively loose compared to the "evaluate during design" approach. The reason why the majority of approaches follow the "evaluate after design" principle is that they all have adopted LCA, the implementation of which in AM requires detailed inventory data and a fully mapped process chain; therefore, LCA can only be executed after the design process or in the later design stage after most decisions have already been made. If the LCA results show that the environmental performance of a design solution is insufficient, the decisions that have been made will need to be repeated and improved, or, in the worst case, the entire design solution will need to be revised. Nevertheless, should designers still attempt to perform LCA in the middle design phase, the only way is to use an LCI database containing inventory data collected from the reference processes of a database provider. However, should the real processes that will be implemented by users differ significantly from the reference processes in the LCI database, the inventory data in the LCI database may deviate significantly from the inventory data of real processes. Consequently, the reliability of LCA results may not be adequate. Given that unique design cases and approaches are encouraged for AM, there is a high possibility that the inventory data from an LCI database will deviate significantly from that of real processes. In addition, the inventory data from different LCI database providers can also differ, and this can lead to greater uncertainty regarding LCA results in the middle design phase. In conclusion, LCA is not an appropriate quantification tool for the middle design phase. As an alternative solution, the energy performance assessment is more suitable for the middle design stage, as it requires neither a full process chain model nor detailed inventory data.

**Assessment of requirement 4: Integrated consideration of design benefits and environmental impacts**

In a few approaches, the integration of design benefits and the environmental impacts of AM is realized in two ways. The first approach is to combine them during the definition of evaluation metrics. An example is the approach of LANTADA ET AL., in which the metric *eco-efficiency* is expressed as the ratios of $CO_2$ emission, material consumption, and energy consumption to costs in the units *kg/€* and *kWh/€* [Lant17]. In the second approach, the design benefits and environmental impacts are still quantified in different metrics but evaluated in a pairwise fashion. An example is the approach of MAMI ET AL., in which environmental impacts and build costs are respectively quantified and normalized [Mami17]. For the evaluation, an *x-y* coordinate is applied, in which the *x* and *y* axes represents normalized environmental impacts and costs, respectively. The economic and ecological performances of design solutions can be described as points on the *x*-*y* plane.

**Assessment of requirement 5: Convenience, ease of use, and robustness**

This requirement is fulfilled in those approaches in which tools are proposed to support the design, quantification, or assessment of eco-design for AM approaches. Examples include the approach of YANG ET AL., in which a part consolidation method is introduced, and that of DESPEISSE ET AL., in which a sustainable value roadmap tool is proposed to identify sustainable business opportunities for AM [Yang19, Desp17]. Moreover, the approach adopted by YANG ET AL. provides a generalized process model in which general steps for executing eco-design for AM are described [Yang19]. This process model improves the general feasibility of their approach, as it can be referred by other designers facing similar problems.

Figure 2-21 and Figure 2-22 below provide an overview of the assessment of the presented approaches.

Question for the evaluation: How much does the following research approach fulfill the requirements for Eco-design for AM frameworks?

● Full fulfillment ◑ Partial fulfillment

◔ Limited fulfillment ○ No fulfillment

Legend:
LCIA: lifecycle impact analysis
FDM: fused deposition modeling
SLM: selective laser melting

| | | | Requirements | | | | |
|---|---|---|---|---|---|---|---|
| | **Authors** | **Research approach** | Description of the environmental performance of AM | Enabling convenient and reliable energy predictions of AM processes | Integration of assessment and design activities | Integrated consideration of design benefits and environmental impacts | Convenience, ease-of-use, and robustness |
| **Unit process inventory and impact** | Balogun et al. | Electricity measurements and $CO_2$-emission modeling and analysis [Balo15] | ● | ○ | ○ | ○ | ○ |
| | Baumers et al. | Electricity measurements and empirical modeling of specific energy consumption and deposition rate [Baum11] | ◑ | ◔ | ○ | ○ | ○ |
| | Baumers et al. | Analytical modeling of the energy use and manufacturing cost and experimental comparison [Baum13] | ◑ | ● | ○ | ○ | ● |
| | Kellens et al. | Electricity measurements and LCIA with ReCiPe [Kell11] | ● | ◔ | ○ | ○ | ○ |
| | Lunetto et al. | Electricity measurements and empirical modeling [Lune20] | ◔ | ◑ | ○ | ○ | ○ |
| | Nagarajan et al. | Electricity measurements, analytical modeling of build time and energy use, and LCIA with ReCiPe [Naga17] | ● | ◑ | ○ | ○ | ○ |
| | Sreenivasan and Bourell | Electricity measurements and LCIA with Eco-Indicator 99 [Sree09] | ● | ○ | ○ | ○ | ○ |
| | Watson and Taminger | Analytical modeling of the energy consumption with respect to the envelope part volume [Wats18] | ◑ | ◑ | ○ | ○ | ○ |
| | Wippermann et al. | Experimental measurements and comparison of different AM machines with a milling machine [Wipp20] | ◑ | ◔ | ○ | ○ | ○ |
| | Xu et al. | Analytical modeling of the energy consumption and experimental comparison [Xu15] | ◑ | ● | ○ | ○ | ● |
| | Yi et al. | Modeling of the energy flow of FDM and SLM, simulation developments, and experimental comparison [Yi20b, c] | ◑ | ● | ○ | ○ | ● |
| **Investigation of the influencing factors** | Baumers et al. | Electricity measurements and evaluation of energy versus the shape complexity [Baum17b] | ◑ | ○ | ◔ | ◔ | ○ |
| | Faludi et al. | Electricity measurements, LCIA based on ReCiPe, and investigation of the most sensitive factors [Falu17] | ● | ○ | ◔ | ◔ | ○ |
| | Griffiths et al. | Electricity measurements of FDM with 4 factorial and 2-level design of experiments [Grif16] | ◑ | ● | ◑ | ○ | ◑ |
| | Kellens et al. | Electricity measurements, LCIA based on ReCiPe with varied nesting efficiency [Kell14] | ● | ◔ | ○ | ○ | ○ |
| | Luo et al. | Analytical modeling of the inventory and environmental impacts, LCIA with Eco-Indicator 95 [Luo99] | ● | ○ | ○ | ○ | ○ |
| | Mognol et al. | Experimental measurements of the energy consumption with varied build orientation [Mogn06] | ◑ | ○ | ◔ | ○ | ○ |
| | Song and Telenko | Analysis of energy waste and environmental impacts of FDM in varied failure scenarios [Song17] | ● | ○ | ○ | ◔ | ○ |
| | Yang et al. | Electricity measurements in factorial design and development of statistical predictive model [Yang17] | ◑ | ● | ◔ | ○ | ◑ |

Figure 2-21: Evaluation of existing approaches (1/2)

Question for the evaluation: How much does the following research approach fulfill the requirements for Eco-design for AM frameworks?

● Full fulfillment ◐ Partial fulfillment

◔ Limited fulfillment ○ No fulfillment

Legend:
LCIA: lifecycle impact analysis
LDD: Laser direct deposition
CM: conventional manufacturing
CED: cumulative energy demand
CExD: cumulative exergy demand
GHG: green house gas
Sus. bus.: sustainable business
circ.econ.: circular economy

| | Authors | Research approach | Requirements: Description of the environmental performance of AM | Enabling convenient and reliable energy predictions of AM processes | Integration of assessment and design activities | Integrated consideration of design benefits and environmental impacts | Convenience, ease-of-use, and robustness |
|---|---|---|---|---|---|---|---|
| Comparison of AM with CM | Faludi et al. | Comparison of FDM and material jetting with milling based on LCIA with ReCiPe [Falu15] | ● | ○ | ○ | ○ | ○ |
| | Huang et al. | Comparison of the primary energy demand and $CO_2$-emissions of aircraft components in AM and CM [Huan16] | ● | ○ | ○ | ◔ | ○ |
| | Kreiger and Pearce | Comparison of CED and GHG of FDM-driven distributed production with conventional scenario [Krei13] | ● | ○ | ○ | ○ | ○ |
| | Le et al. | Electricity measurement and comparison of EBM with milling based on LCIA with CExD and CML 2 [Le17] | ● | ○ | ◔ | ○ | ○ |
| | Morrow et al. | Analytical modeling of the environmental impacts of DMD and comparison with milling [Morr07] | ● | ○ | ◔ | ○ | ○ |
| | Paris et al. | LCIA with cumulated exergy method and CML 2 Baseline 2000 and comparison of EBM with milling [Pari16] | ● | ○ | ○ | ○ | ○ |
| | Priarone et al. | Comparison of the primary energy demand and $CO_2$-emissions of a component in AM and CM [Pria17b] | ● | ○ | ○ | ○ | ○ |
| | Telenko et al. | Electricity measurements and comparison of environmental impacts of SLS with inject molding [Tele12] | ◐ | ○ | ◔ | ○ | ○ |
| | Wilson et al. | Comparison of primary energy demand and $CO_2$-emissions for repair using LDD and casting of a new part [Wils14] | ◔ | ○ | ○ | ○ | ○ |
| Sus. bus. models and circ.econ. | Despeisse et al. | Adaption of sustainable value roadmapping framework, ensuring sustainable business oppotunities of AM [Desp17] | ○ | ○ | ◔ | ● | ● |
| | Ford and Despeisse | Potentials of AM for sustainability and circular economy based on analysis of existing studies [Ford16] | ○ | ○ | ○ | ◔ | ○ |
| | Sauerwein et al. | Potentials of AM for circular economy using qualitative interview with annotated portfolio method [Saue19] | ○ | ○ | ◔ | ○ | ◐ |
| Sustainable design and Eco-design frameworks | Lantada et al. | Improvement of eco-efficiency of SLA through the optimization of support structures [Lant17] | ● | ○ | ◐ | ◐ | ● |
| | Ma et al. | Use of heuristic approach (NSGA-II) to minimize the material cost and energy consumption of SLS [Ma18] | ● | ○ | ◐ | ● | ● |
| | Mami et al. | Modeling of environmental impacts and lifecycle cost, decision-making based on eco-efficiency metric [Mami17] | ● | ○ | ● | ● | ● |
| | Markou et al. | Eco-design for AM framework based on proposed design tools [Mark17] | ○ | ○ | ◐ | ◐ | ● |
| | Priarone and Ingarao | AM process selection tool based on primary energy demand and $CO_2$-emissions [Pria17a] | ● | ○ | ◐ | ◐ | ● |
| | Tang et al. | Integration of topology optimization and LCA into an Eco-design for AM framework [Tang16b] | ● | ◐ | ◐ | ● | ◐ |
| | Yang et al. | Integration of part consolidation and LCA into an Eco-design for AM framework [Yang19] | ● | ◐ | ◐ | ● | ◐ |

Figure 2-22: Evaluation of existing approaches (2/2)

As can be seen from the above figures, none of these approaches fully meet the requirements. Therefore, this dissertation addresses this research gap by developing an eco-design for AM framework that fulfills all of the requirements.

# 3 Research Framework

This chapter describes the research motivations, objectives, and tasks of this dissertation. First, Chapter 3.1 summarizes the important understandings derived from the “State of the Art” chapter based on which the research objectives and tasks are defined and described in Chapter 3.2. Thereafter, Chapter 3.3. describes the structure of the remainder of this dissertation.

## 3.1 Understandings derived from the “State of the Art” chapter

Fundamental insights regarding AM technologies, including their general and environmental properties, and eco-design for AM can be drawn from the “State of the Art” chapter. The most important understandings can be summarized as follows:

- AM represents an alternative to conventional manufacturing methodologies and can be used to produce components with complex geometries. AM offers revolutionary benefits such as design freedom, production network and supply chain reorganization, and innovative business models.
- Due to advances in mechanical engineering and material science, modern AM processes are capable of processing metal parts that provide long-term functional use. Therefore, the application focus of AM has shifted from rapid prototyping to rapid manufacturing and rapid MRO.
- AM is considered as a cleaner production technology given its capability for lightweighting and process chain shortening, as well as its other environmental benefits. However, critics also argue that the environmental benefits of AM should be more critically investigated because the environmental performance of AM is an extremely complex phenomenon, and AM may exhibit disadvantages in different life stages.
- A most promising solution to ensure the environmental benefits of AM is eco-design, in which the environmental performance of a design solution is considered and improved in the design stage of an AM product lifecycle.
- General eco-design can be discussed at the levels of system and success, strategies, actions, and tools. On the manufacturing level, eco-design for AM approaches are mainly discussed on the levels of actions and tools.
- The concept of eco-design for AM is derived from the interactions among the manufacturing, product lifecycle, and sustainability domains. Eco-design for AM implies a holistic methodology in which AM, design, and environmental issues are considered.
- In existing approaches, the environmental performance of AM is mainly analyzed using LCA and energy performance evaluation. In AM, energy use is the major factor in terms of causing environmental impacts.
- The energy consumption of an AM process can be predicted using either an empirical or a physical method. The empirical method determines the energy consumption of AM based on hypothetical variables and parameters that are observed from outside of the AM system (the black box principle), while the physical method determines the energy consumption of AM based on system parameters that are observed from inside of the system (white box principle).
- In the LCA-based eco-design for AM approaches, design and assessment activities are separated or only loosely integrated, as LCA requires detailed inventory data and full process chain descriptions and can only be executed after the design process or in the later

design stage (the "evaluate after design" principle). A superior approach is to use energy performance assessment, which enables simultaneous assessment and design (the "evaluate during design" principle).

- In existing eco-design for AM approaches, the integrated consideration of design benefits and environmental impacts can be performed in one of two ways. Either design benefits and environmental impacts are described in a single metric, usually expressed as a ratio, or design benefits and environmental impacts are expressed in different metrics but are evaluated in a pairwise form.
- The development of tools or generalized process models to support quantification, design, assessment, or other activities within an eco-design for AM framework can significantly improve that framework's usability and robustness in dealing with individual design cases.

In summary, eco-design for AM is a key factor in investigating, assessing, and ensuring the environmental benefits of AM. A general eco-design for AM approach should fulfill the following requirements: It should be able to describe environmental performance and to make energy consumption predictions, feature integrated design and assessment, allow for the consideration of the environmental impacts of designs, and offer convenient and robust usability. However, while the approaches found in the literature satisfy one or less of these requirements, none of them fully satisfy all of these requirements. Therefore, based on these findings, the research objectives and tasks of this dissertation are identified and described in the next subsection.

## 3.2 Research objective and tasks

### 3.2.1 Objective and scope

In line with the observations presented above, the research objective of this dissertation is defined as the development of an eco-design for AM framework aimed at the middle design stage based on energy performance quantification and assessment. In this statement, two issues are identified as being within the scope of this research: the "middle stage" and "energy performance." This statement of the objectives of this research is based on the following hypotheses:

**Hypothesis 1: The design process of AM can be expressed in three stages and seven phases**.

As shown in Figure 3-1, this dissertation expresses the design process with AM in three stages and seven phases: the *early stage*, in which customer and market requirements are analyzed and general product ideas are created; the *middle stage*, in which the specific functional and geometrical features of a product are defined, the AM system for handling the production tasks is designed, and the build process based on the product and AM system is defined; and the *late stage*, in which the process chain with AM on the factory level and the entire production network are defined.

**Hypothesis 2: In eco-design for AM, it is preferable to integrate evaluation activities in the middle stage rather than the early or late stages.**

In this dissertation, the focus is on the middle phase of eco-design for AM. The other two design stages are omitted due to the following two reasons: First, the middle stage is more suitable than the late stage for executing performance evaluation because earlier identification of environmental problems implies the saving of development time and costs. If the evaluation and improvement are performed in the later stage, the potential benefits of doing so in the middle stage will be lost. Second, it is preferable to engage in eco-design for AM in the middle stage than the early stage because, in the early stage, rough product ideas are abstract, and there are not enough data for a quantitative performance evaluation.

**Hypothesis 3: In the middle stage, energy performance assessment is more suitable than LCA**.

As discussed previously, LCA requires detailed inventory data of the full process chain with AM, which means that this assessment approach is more suitable for the late design stage. Should designers attempt to perform LCA in the middle design stage, they will need to use an LCI database, which may lead to unreliable quantification results. Therefore, this dissertation adopts energy performance assessment, which, as depicted in Figure 3-1, can be performed based on the predicted energy use of AM on the unit process level in the middle design stage.

**Hypothesis 4: The assessment and improvement of energy performance can be equivalent to the assessment and improvement of environmental performance**.

Since energy use interacts with other environmental impacts of AM, more energy use implies more environmental impacts. As discussed previously, the electricity use of AM shares 80% of the embodied energy and causes up to 75% of cradle-to-gate environmental impacts of AM. Therefore, this dissertation assumes that the evaluation and improvement of energy performance can be considered equivalent to the evaluation and improvement of the entire environmental performance of AM.

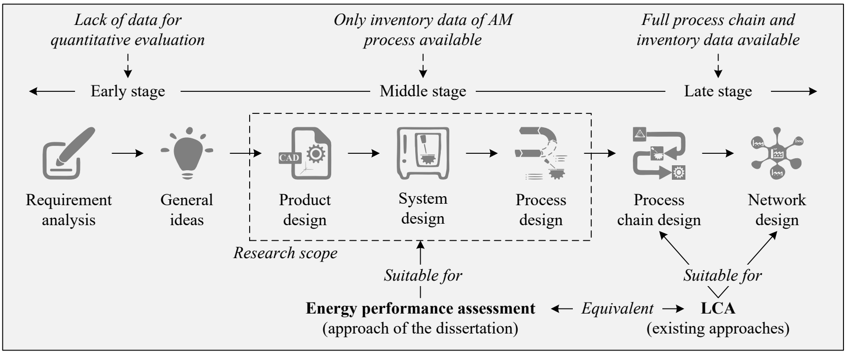



Figure 3-1: Design process with AM and research scope of the dissertation

### 3.2.2 Research tasks

Based on the defined research objective, scope, and hypotheses, four research tasks are defined; these tasks are depicted in Figure 3-2 and described in the following paragraphs.

**Research task 1: Development of a tool for the prediction of energy consumption of AM**

The first research task is to develop an energy prediction tool that enables the convenient and reliable quantification of the energy consumption of users in the middle design phase. This task is defined based on Requirements 3 and 5 (see Chapter 2.3.3), which respectively state that general eco-design for AM approaches should enable the prediction of energy consumption of AM and offer convenient usability. To accomplish this task, this dissertation adopts a physical approach in which the system components of AM systems are specified and energy flows between the system components are analyzed and modeled. Thereafter, a simulation tool is developed based on the MATLAB/Simulink platform. The functional logic of the simulation follows the *NC code and database-driven* approach, which is introduced in Chapter 4.4. To verify the reliability of the simulation, experiments are performed, and the results thereof are compared with those of simulations.

**Research task 2: Development of a model for the assessment of the energy performance of AM**

The second research task seeks to propose a model to describe the energy performance of AM, as Requirements 1 and 4 (see Chapter 2.3.3) respectively stress that general eco-design for AM approaches should describe the environmental performance of AM and enable a combination of design benefits and environmental performance. To accomplish this task, this dissertation proposes a *multidimensional energy performance assessment model* based on energy performance indicators, which are defined by combining the energy-related and performance-related metrics of AM-specific design solutions.

**Research task 3: Integration of the prediction tool and assessment model into a holistic eco-design for AM method**

Following the development of the prediction tool and assessment model, the third task aims to combine them into a holistic method for carrying out eco-design for AM based on energy performance assessment. The definition of this task respects Requirements 3 and 5, which concern the integration of design and assessment and convenient and robust usability, respectively. In this dissertation, the proposed method is presented in the form of a generalized process model that describes the necessary specification, design, quantification, and assessment activities with the support of the developed prediction tool and assessment model. The proposed method can be used as a guideline for other users facing design and environmental issues associated with AM.

**Research task 4: Validation of the proposed method**

The last task aims to validate the proposed method in different use cases to ensure that all the requirements identified in Chapter 2.3.3 are fulfilled and that the feasibility of the prediction tool, the assessment model, and the generalized process model for eco-design for AM is confirmed.

Figure 3-2 provides an overview of the motivations, objective, and tasks of the dissertation.

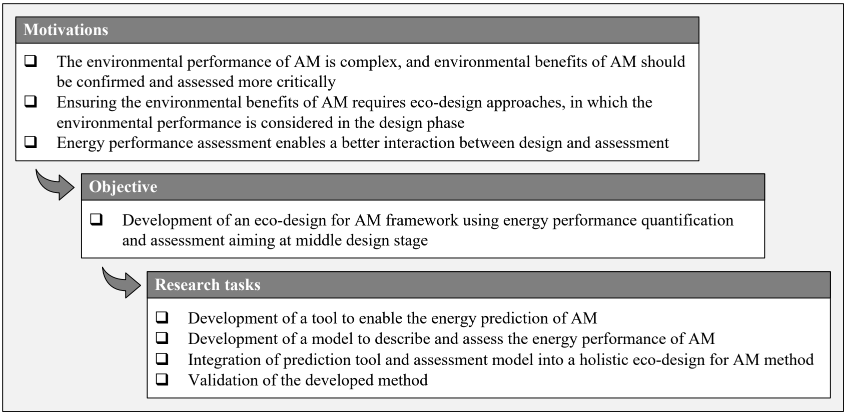



Figure 3-2: Motivations, research objective and tasks of this dissertation

## 3.3 Structure of the remainder of the dissertation

With the exception of the final summary and outlook chapter, the remainder of the dissertation comprises four main chapters, as four research tasks are defined. In each main chapter, the procedure for and results of accomplishing a specific research task are introduced. The arrangement of the remaining chapters is illustrated in Figure 3-3 and described below.

- Chapter 4 describes the approach used to develop the energy simulation tool for AM. The first step of the development approach is a system exploration in which the system components of an AM system are identified and their functions are analyzed. Thereafter, the energy flows among the system components are modeled using a bond graph method. Based on the energy model, a simulation tool is developed, and experiments are carried out to verify the simulation accuracy of the tool.
- Chapter 5 introduces a *multidimensional energy performance assessment model* of AM. Thereafter, the assessment method based on the proposed model is explained, in which *normalization*, *pairwise comparison*, and *aggregation* techniques are applied.
- Chapter 6 describes a method for carrying out eco-design for AM based on energy performance assessment, in which the developed simulation tool and assessment model are integrated. The method is presented in the form of a generalized process model that features five main phases: situation analysis, topology optimization, AM workstation design, build process design, and EnPI-based assessment.
- To demonstrate the feasibility of the proposed method, three use cases are performed and described in Chapter 7.
- Chapter 8 presents a summary and outlook of the research presented in this dissertation.

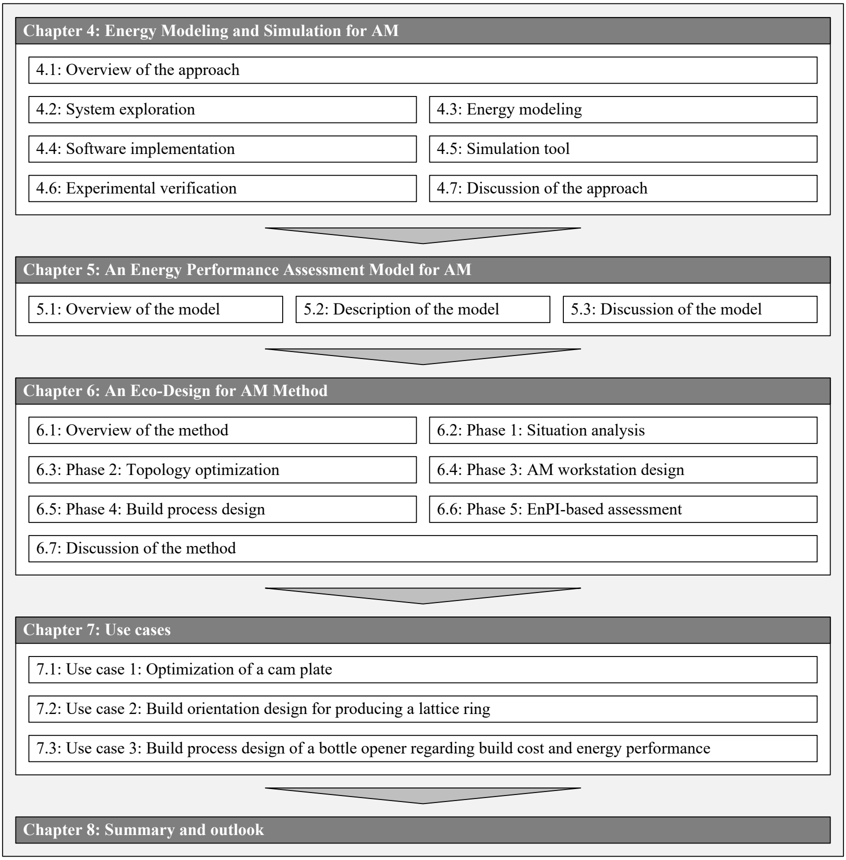



Figure 3-3: Structure of the remaining chapters of the dissertation

# 4 Energy Modeling and Simulation for AM

This chapter describes the approach for the energy modeling and simulation implementation of AM, which is divided into five main parts: system exploration, energy modeling, software implementation, simulation tool, and experimental verification. Chapter 4.1 presents an overview of the approach, and Chapters 4.2 to 4.6 describe each of the main parts in detail. Finally, Chapter 4.7 presents a discussion of the development approach.

## 4.1 Overview of the approach

Figure 4-1 presents an overview of the approach for energy modeling and simulation implementation, as well as the layout of the subsections. The first step of the approach is the system exploration, which is introduced in Chapter 4.2. In the system exploration step, the system boundaries of the AM process are first defined. Based on the defined system boundaries, the composition and functions of the system are specified, and the datasheets of AM machines and peripheral units are collected. Chapter 4.3 describes the energy modeling step, which is divided into power flow modeling and time modeling. In this phase, the power flow modeling aims at the description of the power transfer and consumption of the system components, and the time modeling focuses on the description of the work status and times of the system components. Chapter 4.4 describes the software implementation, in which simulation software is developed based on the power model and time model. At the core of the simulation is a *Numerical Control (NC) code and database-driven approach* in which time parameters are extracted from the NC code and the power parameters of system components are generated from a power database. The result of the software implementation is a simulation tool, the architecture and graphical user interface (GUI) of which are described in Chapter 4.5. Chapter 4.6 describes the process used to verify the accuracy of the simulation, in which experiments are performed and the results thereof compared with those of simulations.

For a better understanding, the modeling and simulation implementation steps are explained based on the research of the SLM process, in which the SLM machine is the *Concept Laser Mlab* at TU Kaiserslautern [Conc19a].

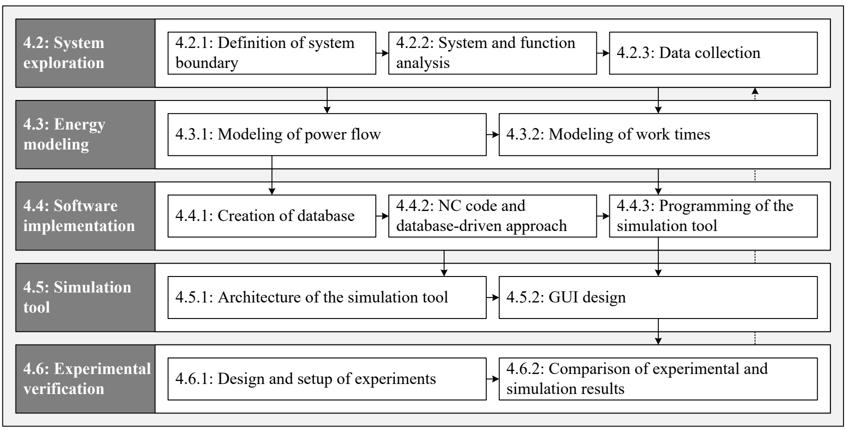



Figure 4-1: Overview of the energy modeling and simulation implementation approach

## 4.2 System exploration

### 4.2.1 Definition of system boundary

In general, manufacturing consists of six hierarchical levels: the *manufacturing network* level, the *manufacturing location* level, the *manufacturing segment* level, the *manufacturing system* level, the *manufacturing cell* level, and the *workstation/machine* level (see Figure 4-2 [West00]). According to ISO 14955-1, at the workstation/machine level, the system boundary for the environmental evaluation of a machine tool shall include the machine tool itself and its peripheral units, and the system components refer to the mechanical, electrical, hydraulic, or pneumatic devices or a combination thereof within the system boundary [ISO17]. According to ISO/ASTM 52900, an AM system is the system of AM machine and its auxiliary equipment used for AM [ISO15b]. Therefore, by combining the ISO 14955-1 and ISO/ASTM 52900 standards, the system boundary of an AM process can be considered to be equivalent to an AM system consisting of an AM machine and its accessories (see Figure 4-2). To analyze and quantify the energy performance of the system, energy flows in and out of the system boundaries (e.g., electricity, heat exchange, and protection gases) should be considered.

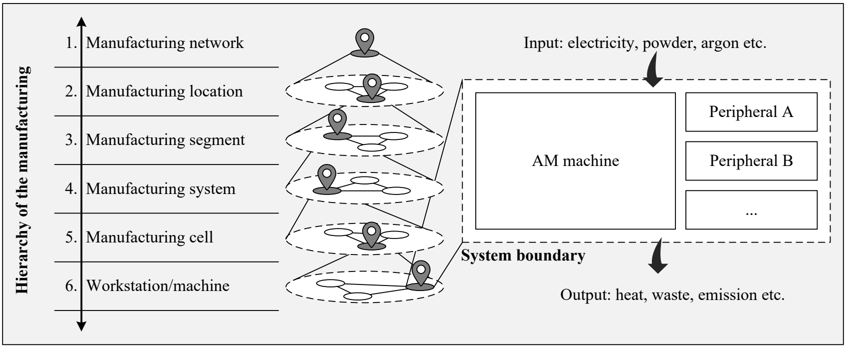
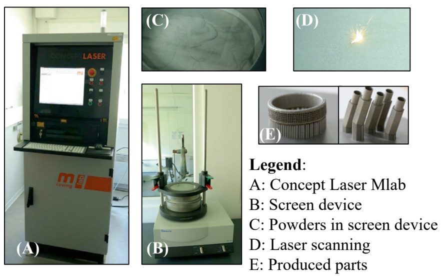



Figure 4-2: Definition of the system boundary of an AM process

Figure 4-3A and B present photographs of the *Concept Laser Mlab* machine and a screen device, respectively. Before the SLM process is performed, the metal powder must be screed by a sieve net of a certain diameter using high-frequency oscillation (see Figure 4-3C). Otherwise, the heterogeneous particle size will result in produced parts with a lower material density. The *Concept Laser Mlab* offers three types of build platforms and can process different types of materials, including steel, aluminum, titanium alloy, gold, and other metal powders. The layer thickness can be defined from 15 to 50 µm. The laser power is up to 100 W, and the scan speed can be up to 7 m/s. During the build process, the laser beam creates a high-temperature molten pool on the powder bed, which, as shown in Figure 4-3D, causes small sparks. After the build process, the remaining powder can be recycled, screened, and reused. The support structure for parts, which are depicted in Figure 4-3E, must be removed, and the parts can be post-processed and then used directly. The material density of finished parts is generally higher than 99.5%, which is comparable or even superior to the performance of a cast part [Wohl19]. The accuracy of the production of a component from a CAD model to a final product ranges from -0.05 to +0.05 mm, and the surface quality of a finished part (Ra) varies from 4.5 to 7 µm [Wohl19].

**Concept Laser Mlab and peripherals**




**Data of Concept Laser Mlab**

| | |
|---|---|
| **Build size:** | 50×50 mm² (x, y)<br>70×70 mm² (x, y)<br>90×90 mm² (x, y)<br>z= 80 mm |
| **Layer thickness:** | 15 to 50 µm |
| **Laser power:** | 100W |
| **Scan speed:** | max. 7 m/s |
| **Power:** | max. 1.5 kW |
| **Inert gas:** | Nitrogen or Argon |
| **Dimension:** | 705×1848×1220 mm (W×H×D) |
| **Materials:** | Steel, aluminum, titanium alloy, etc. |

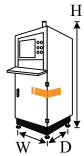



Figure 4-3: The Concept Laser Mlab and its technical data

### 4.2.2 System and function analysis

A function is a property of a system or component in which input is processed or converted to output [Ropo09]. A function can be neutral and independent of the system design, and it can be derived directly from the customer's needs. Therefore, function-oriented system modeling and description are widely used in the development of complex technical systems [Feld13]. In the evaluation of the energy performance of machine tools, function-oriented system analysis can be used to determine which system components have functions related to energy use [Gont11]. To facilitate a more convenient identification and clustering of the system components of an AM system, the following five generalized function categories are defined:

- **Material processing**: Material processing describes the binding of materials using a specific binding mechanism and summarizes the functions thereof (e.g., generation of a laser beam or electron beam, control/movement of the print head of an FDM printer).
- **Material feeding**: Material feeding describes the feeding of materials for processing and summarizes the functions thereof (e.g., powder spreading, filament feeding, rolling of a material reel, feeding of arc wire).
- **Process conditioning**: Process conditioning aims at the creation of a stable manufacturing environment for the processing of material and summarizes the functions thereof (e.g., machine vacuuming, circulation of protective gas, failure detection, process monitoring).
- **Material preparation/recycling**: Material preparation/recycling refers to the operations for preparing and recycling materials before and after the manufacturing process and summarizes the functions thereof (e.g., powder screening and recycling, scrap cleaning).
- **Cooling/heating**: Machine cooling/heating refers to the heating and cooling of AM machines and summarizes the functions thereof (e.g., pre-heating/cooldown of a build platform, cooling of a build cabinet).

For the function analysis, the subfunctions of the AM system are first defined based on the five function categories. Thereafter, the system components of the AM system are identified and assigned to the defined subfunctions. Figure 4-4 shows the system and function analysis of the *Concept Laser Mlab*, in which the main function of the SLM machine is defined as the melting and adding of powders into a solid part. The main function is then decomposed into subfunctions based on the five general function categories, and the system components associated with the functions are identified.

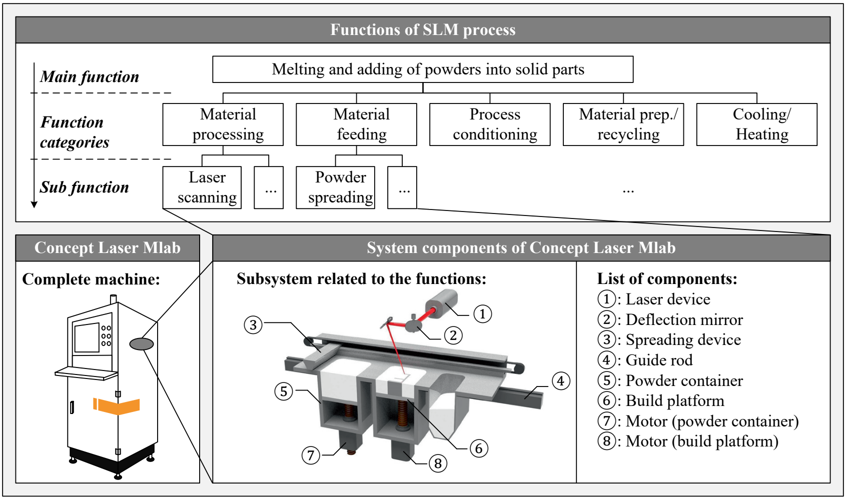



Figure 4-4: Function-oriented clustering of the system components of the Concept Laser Mlab

Table 4-1 presents a list of the system components of *Concept Laser Mlab*, which are defined according to their functions. In addition, the energy domains associated with the system components are also described in the system analysis, as doing so facilitates the energy modeling in the subsequent steps. For example, the electrical and thermal domains are noted as being linked to material processing, as all devices consume electricity and have heat loss. In addition, the mechanical domain is associated with material processing, as the deflection device comprises servo motors to enable the motion of the laser beam.

| Function category | Function | System components | Related energy domains |
|---|---|---|---|
| Material processing | Laser scanning | Laser device | Electrical, mechanical and thermal |
| | | Powder bed | |
| | Deflection | Deflection device | |
| | Process control | CNC-module | |
| Process conditioning | Vacuuming | Vacuum pump | Electrical, mechanical, pneumatic and thermal |
| | Gas filling | Gas tank | |
| | Gas circulation | Circulation fan | |
| | | Gas sensor | |
| Material feeding | Movement of build platform | Motor for build platform | Electrical, mechanical and thermal |
| | Movement of powder container | Motor for powder container | |
| | Movement of spreading-device | Motor for powder-spreading device | |
| Material preparation/ recycling | Powder screening | Screen device | Electrical, mechanical and thermal |
| | Powder recycling | Vacuum cleaner | |
| Cooling/Heating | Cooling | Cooling device | Electrical, mechanical, pneumatic and thermal |

Table 4-1: List of functions and system components of the Concept Laser Mlab

### 4.2.3 Data collection

The final step in the exploration of the studied AM system is to collect data related to the system's components, functions, and energy consumption. In addition to the list of system components presented in the previous subsection, other system documents include, but are not limited to, for example, product descriptions, material sheets, circuit diagrams, and the research literature on the AM system (see Figure 4-5.)

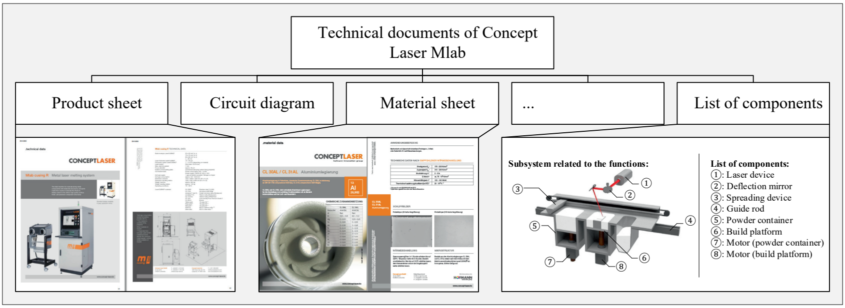



Figure 4-5: Technical documents for the Concept Laser Mlab

## 4.3 Energy modeling

### 4.3.1 Modeling of power flow

Energy is the time integral of power; therefore, the energy modeling of an AM system can be divided into the modeling of the power flow between the system components and the modeling of the work status and times of the system components.

For the power modeling, the *bond graph* methodology is used. This methodology is employed for two reasons. First, bond graphs are graphical representations of system models that are more suitable for human perception than oral or textual representations [Boru10]. Second, bond graphs feature a uniform terminology for describing power exchange between different energy domains, such as the hydraulic, mechanical, and electrical domains [Karn12]. In a bond graph, the power ($P$) flowing from one system into another system is regarded as the product of an effort variable ($e$) and a flow variable ($f$), which is expressed as Equation 4-1:

$$P = e \times f \qquad \text{Equation 4-1}$$

The effort and flow variables have different interpretations in different energy domains (e.g., in translational mechanics, the effort and flow are force and velocity, respectively, and, in the electrical domain, the effort and flow are voltage and current, respectively. For more information concerning the bond graph method, see Appendix A and the works of KARNOPP, BORUSKY, and THOMA [Karn12, Boru10, Thom00]).

Figure 4-6 depicts the bond graph of the cooling function for the *Concept Laser Mlab*. The cooling function is provided by an external air conditioner, which continuously draws heat out of the machine and into the surrounding room, thus keeping the interior environment of the machine at a constant temperature. The functional logic of the external air conditioner can be ideally described as the vaporization-condensation cycle of a refrigerant, as depicted in the circuit diagram in Figure 4-6. First, the refrigerant expands from the liquid to the gaseous state and then absorbs the heat from inside of the machine. Thereafter, the vaporized refrigerant is compressed and condensed to a liquid state and then distributes heat into the room. The liquid refrigerant will subsequently vaporize again to perform another cooling cycle. To map the power flows as well as to create the bond graph, the related power variables are defined and allocated to the system components or the condensate (i.e., $u$ and $i$ represent the voltage and current of the motor to drive the compressor, and $\tau$ and $\omega$ represent the torque and angular velocity of the motor).

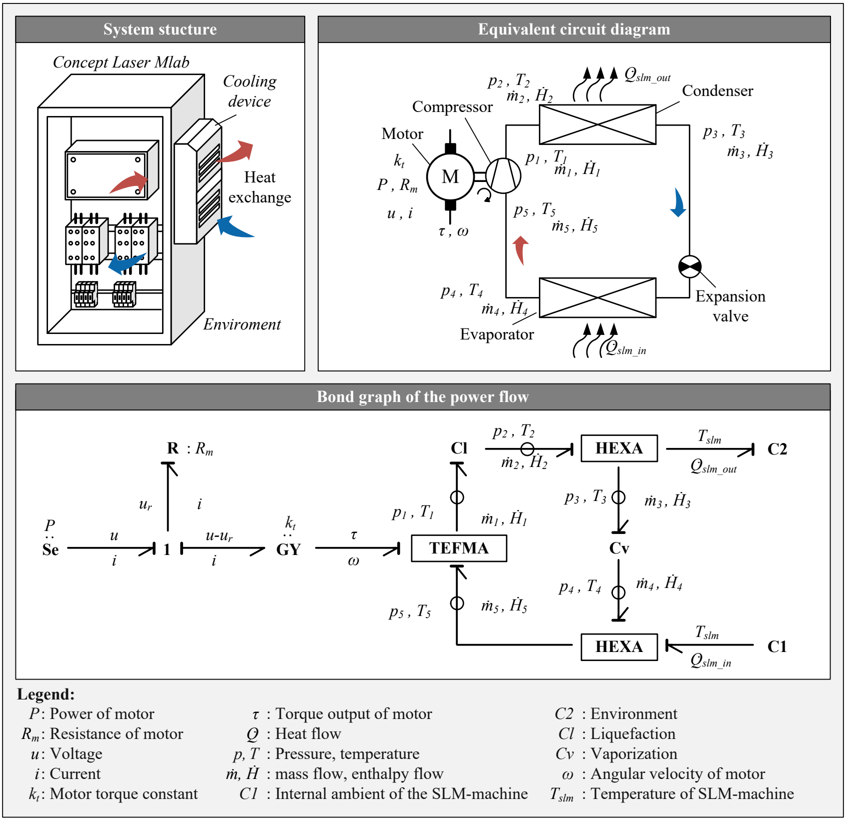



Figure 4-6: Bond graph of the cooling function of the Concept Laser Mlab

In the bond graph of Figure 4-6, the bonds with half-arrows refer to the direction of the power flow from one port to another port. In a bond graph, a port describes the place where subsystems or system components can be connected to allow power flows [Karn12]. Initially, port **Se** represents the power supply of the motor used to drive the compressor, the determination of the electricity consumption of which requires the effort and flow variables of voltage $u$ and current $i$. Thereafter, the power flows from **Se** to the port **1**-junction, where the flow variable $i$ is conserved and the effort variable $u$ is distributed. A part of the power flows from **1**-junction to port **R**, which represents the power loss of the motor with the equivalent resistance $R_m$. The remaining power flows from **1**-junction to port **GY**, which is an abbreviation of the term *gyrator*. A gyrator defines the conservation of power flow, where the effort on the input bond is the constraint to the flow on the output bond. The gyrator is required to represent the change of the energy domains of specific energy transmission systems. In this bond graph, the motor converts the electricity into the rotation of the compressor and should be represented by port **GY** because the torque $\tau$ is the product of the motor torque constant $k_t$ and the current $i$. Thereafter, the power flows from port **GY** to port **TEFMA**, which is an ad hoc port representing a turbomachine [Thom00]. In this bond graph, port **TEFMA** represents the compressor, where the power flows out of the port is the sum of the power input from ports **GY** and **HEXA**. It should be noted that the bonds with a circle in the middle indicate a power exchange associated with matter exchange. In this bond graph, matter exchange refers to the circulation of the refrigerant. Because the refrigerant is compressible, its power exchange with other ports should be expressed by liaison variables using the *Eulerian* reference frame in thermodynamics [Thom00]. This means that the pressure and mass flow ($p$, $\dot{m}$) describe hydraulic power, while the temperature and enthalpy flow ($T$, $\dot{H}$) describe thermal power. According to the bond graph terminology, the pressure and temperature variables ($p$, $T$) are combined to represent the effort, while the mass flow and enthalpy flow ($\dot{m}$, $\dot{H}$) are used to represent the flow. Note that neither the product of a pressure variable and a mass flow variable nor the product of a temperature variable and an enthalpy flow variable is the power, which indicates a pseudo bond graph [Thom00]. The ports **Cv** and **Cl** indicate the liquefaction and vaporization of the refrigerant, respectively. In this bond graph, the power flowing from port **TEFMA** to port **Cl** describes the condensation of the compressed vapor refrigerant. Thereafter, the power ($\dot{Q}_{slm\_out}$) flows to the multiport **C2,** which represents the room, via port **HEXA**, which describes the heat exchange between the liquid refrigerant and the room. Following port **HEXA**, the power flows to port **Cv**, indicating the vaporization of the liquid refrigerant. The vapor refrigerant subsequently flows to a second port **HEXA**, which represents the absorption of the heat from the SLM machine ($\dot{Q}_{slm\_in}$). Finally, the vapor refrigerant flows to port **TEFMA**, which again indicates the compression again and a new vaporization-condensation cycle. Figure 4-6 shows the system model and the bond graph for the cooling function, and the entire bond graph for the *Concept Laser Mlab* is provided in Appendix B.

After the power flows among individual system components are mapped using bond graph, the power consumption model of the *Concept Laser Mlab* can be created using the bottom-up approach. First, the power consumption for each function category ($P_{fun}$) is the sum of the power consumption of the system components ($P_{com}$) that are assigned to this function category, and it is given by Equation 4-2, in which $k$ represents the total number of the system components allocated to this function category:

$$P_{fun} = \sum_{n=1}^{k} P_{com(n)} \qquad \text{Equation 4-2}$$

The total power consumption model of the *Concept Laser Mlab* ($P_{SLM}$) is the sum of the power consumption of the five function categories, and it is expressed as Equation 4-3:

$$P_{SLM} = \sum_{n=1}^{5} P_{fun(n)} \qquad \text{Equation 4-3}$$

### 4.3.2 Modeling of work times

The SLM process ($t_{SLM}$) on the workstation/machine-level is divided into three subphases: the *pre-step* ($t_{pre}$), which summarizes the operations of system components before layers are deposited (e.g., powder screening, vacuuming, and system calibration); the *in-step* ($t_{in}$), which summarizes the operations that occur during the build of layers (e.g., laser scanning of layers, cooling process, and gas circulation); and the *post-step* ($t_{post}$), which summarizes the operations that occur after the build of layers (e.g., cooldown, as depicted in Figure 4-7). In summary, the time required for an SLM process can be expressed using Equation 4-4:

$$t_{SLM} = t_{pre} + t_{in} + t_{post} \qquad \text{Equation 4-4}$$

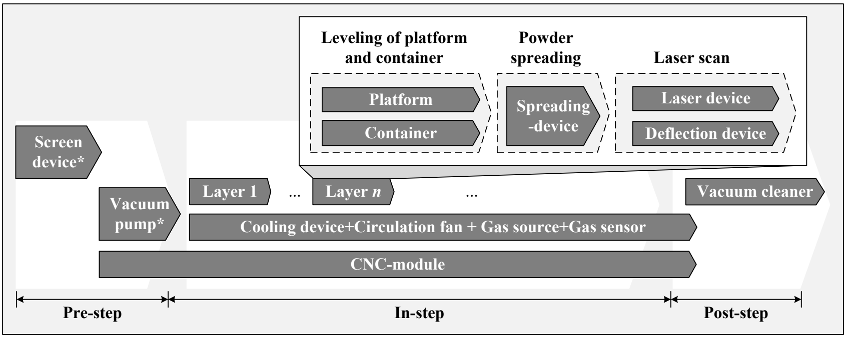



Figure 4-7: Time model of the SLM process

The time required for the *pre-step* ($t_{pre}$) is the sum of the operation times for the powder screening ($t_{ps}$), vacuuming ($t_{vac}$), and system calibrating ($t_{cal}$), which is defined in Equation 4-5:

$$t_{pre} = t_{ps} + t_{vac} + t_{cal} \qquad \text{Equation 4-5}$$

During the *in-step*, the system components such as the cooling device and CNC module function continuously, while other system components, such as the spreading device, platform, and laser device, function discretely during the process of each layer. The *in-step* subphase can be further divided into three operations: leveling of the platform and container ($t_{lpc}$), powder spreading ($t_{ps}$), and laser scanning ($t_{ls}$). Thus, the time required for the *in-step* can be defined by Equation 4-6, in which $k$ represents the total number of layers:

$$t_{in} = \sum_{n=1}^{k} t_{layer(n)} = \sum_{n=1}^{k} (t_{lpc(n)} + t_{ps(n)} + t_{ls(n)}) \qquad \text{Equation 4-6}$$

In the *post-step*, the build chamber is cooled down and the powder is recycled. Thus, the time of post-step ($t_{post}$) can be expressed as Equation 4-7, in which $t_{cd}$ and $t_{cle}$ represent the time required for the cooldown and powder recycling, respectively:

$$t_{post} = t_{cd} + t_{rec} \qquad \text{Equation 4-7}$$

The work status of system components can vary in different operations. In the approach to the energy modeling and simulation of this dissertation, the work status of a system component is ideally assumed to be one of two possibilities: *in operation* and *standby/shutdown*. The *in operation* status implies that the system component is working, consuming power, and providing specific functions, while, in *standby/shutdown*, the system component is assumed to consume no power. Based on this assumption and the time model described above, the work status of each system component is summarized in Table 4-2, in which the value 1 represents the status "*in operation*" and value 0 represents the status "*standby or shutdown.*"

| Work status<br>1: in operation<br>0: standby/shutdown | SLM process on workstation/machine-level | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Pre-step | | | In-step | | | Post-step | |
| System components | Powder screening | Vacuum-ing | Calibrate | Laser scan | Platform move | Powder spread | Cool down | Cleaning |
| Laser device | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Powder bed | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| Deflection device | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| CNC-module | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| Vacuum pump | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gas tank | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| Circulation fan | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 |
| Gas sensor | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| Motor (build platform) | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Motor (powder container) | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Motor (powder-spreading) | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Screening device | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Vacuum cleaner | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Cooling device | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |

Table 4-2: Work status of system components in the SLM process

## 4.4 Software implementation

### 4.4.1 Creation of database

In general, power data can be obtained either by experiments or simulations. This dissertation adopts the simulation method because it is convenient and fast. First, equivalent simulation models of all system components are created using MATLAB/Simulink based on the bond graphs [Math19]. The results of the Simulink models are exported in the form of *.mat* files that form the database for the *Concept Laser Mlab*, as shown in Figure 4-8.

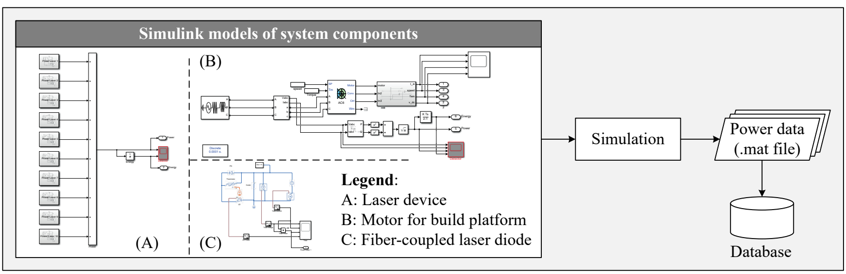



Figure 4-8: Creation of a database using MATLAB/Simulink

### 4.4.2 NC code and database-driven approach

In conventional manufacturing, simulations or calculations of the energy use of machine tools based on NC code are more precise than calculations without the use of NC code [Zhou16]. Given this fact, this dissertation proposes the *NC code and database-driven approach*, in which the simulation is based on the time parameters extracted from the NC code of a build task and the power data of the system components from a database.

In the development case of the *Concept Laser Mlab*, the NC code file containing the process information is exported from the *Autodesk Netfabb* software [Auto19]. After the process preparation, in which the layer thickness, laser speed, scan patterns, and other process parameters are defined, an *.lsr* file can be exported. The *.lsr* file contains all the process information of the build task (see Figure 4-9). In each line of the *.lsr* file, the scan path of a laser beam is defined. In the example of Figure 4-9, the first scan path of layer 1059 is highlighted, in which the first coordinate ($x_0$, $y_0$, $z_0$) represents the position of the current laser beam, while the second coordinate ($x_1$, $y_1$, $z_1$) represents the target position to which the laser point will move. The two numbers after the coordinate ($x_1$, $y_1$, $z_1$) are the laser speed ($s_{laser}$) and current time ($t_{current}$), respectively.

As depicted in Figure 4-9 and described below, the functional logic of the *NC code and database-driven approach* can be explained in five steps with one decision gateway:

- **Step 1: Read time parameters**. In general, NC codes are text files, including the *.lsr* file used in this approach. The first step of the *NC code and database-driven approach* is to extract the time parameters from the NC code. For example, in the case of the *Concept Laser Mlab*, a program that extracts the last number of each line in an *.lsr* file is written in MATLAB.
- **Step 2: Generate a time array**. Based on the extracted time parameters, a time array is created using a specific sampling time. For example, as shown in Figure 4-9, it is assumed that the time parameter for processing the first layer is 10 s and that the sampling time is 1 s. Thus, numbers from 1 to 10 are added to the time array, with each number representing a point in time. Furthermore, the attributes of the points in time are noted. In the example, the numbers from 1 to 10 are the *times for layer 1*. In the 10 s, numbers from 1 to 5 are the *times in which the laser scans*, while 6 to 10 are the *times in which the platform moves*.
- **Step 3: Check work status**. In this step, the work status of each system component at each point in time of the time array is determined based on Table 4-2. For example, the laser device generates the laser beam used to scan the powders. Thus, during the *laser scan* phase, the laser device is *in operation* (work status = 1), while, during the operation platform move, it is on *standby* (work status = 0). Depending on the work status, the next steps will differ, as indicated by the decision gateway in Figure 4-9.
- **Step 4.1: Generate power values from the database**. If the work status of a system component in a specific phase is "1," the power of the system component ($P_t$) at each point in time ($t$) in this phase will be generated from the database. The power can be determined using Equation 4-8, in which the aggregate $D$ represents the database and contains the power data for this system component.

$$P_t \leftarrow P_i \text{ in } D = \{P_i, i \in N^*\} \qquad \text{Equation 4-8}$$

- **Step 4.2: Set power values to zero**. If the work status of a system component is "0" in a phase, its power values in this phase are set as zero, as indicated by Equation 4-9:

$$P_t \leftarrow 0 \qquad \text{Equation 4-9}$$

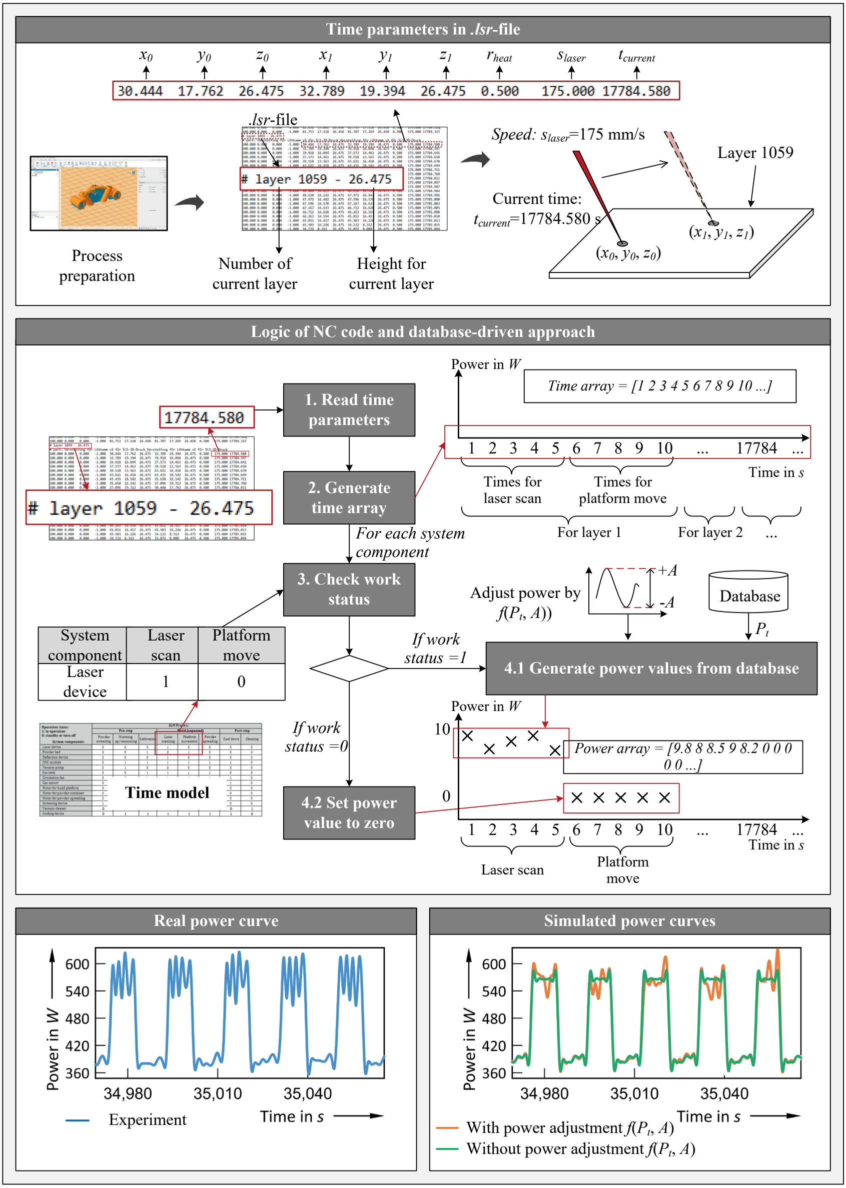



Figure 4-9: The NC code and database-driven simulation approach

After the power values of a system component are generated for each phase, they can be arranged as a power array whose length is equal to that of the time array. The power arrays of all system components are added to the power array of the entire AM system as defined by Equation 4-3.

Finally, the energy consumption of the entire system ($E$) can be calculated through a trapezoidal numerical integration of the power array ($P$) with the time array ($T$), as defined in Equation 4-10:

$$E = \int_0^T P(t)dt \cong \sum_{k=1}^{T} \frac{P(k-1)+P(k)}{2} \Delta t \qquad \text{Equation 4-10}$$

It should be noted that the database-driven simulation approach has an issue in that the generated power curve does not appear to match the actual power curve. For example, in the blue power curve (obtained from the experiment in Chapter 4.6) at the bottom left of Figure 4-9, the peaks and valleys represent the *laser scan* and *platform move* (including *powder spreading*) phases, respectively. The green power curve at the bottom right of Figure 4-9 is the simulated power curve based on Equation 4-8. Each peak and valley on the blue power curve look different, while the peaks and valleys on the green power look the same. This is because the power values in the database are always the same. For each layer and each *laser scan* and *platform move*, the same power data are generated and plotted. A similar issue can be found in the study conducted by XU ET AL. [Xu15]. To create a more realistic power curve, the approach of this dissertation adopts a method that involves adding random numbers to adjust the power values generated from the database. The core idea is to assume a constant $A$ that describes the range of the power values of a real AM process, as shown in Figure 4-9. Based on Equation 4-8, the power of a system component ($P_t$) at a point in time $t$ can be given by Equation 4-11, in which $f(P_t, A)$ is the adjustment function for power values and $r$ is a random number that should be generated from the range [-A, A]. For different cases, the constant A should be defined individually.

$$P_t \leftarrow f(P_t, A) = P_t + r, \text{with } r \in [-A, A] \qquad \text{Equation 4-11}$$

The orange power curve at the bottom right of Figure 4-9 shows the simulated power curve based on Equation 4-11 and demonstrates a more realistic behavior than the blue curve. Nevertheless, a concern regarding the use of the power adjustment function $f$ is that it may have an impact on simulation accuracy. However, based on the experimental verification, it is concluded that this impact is negligible, as is discussed in Chapter 4.6.2.

### 4.4.3 Programming of the simulation tool

In the development case of the Concept Laser Mlab, MATLAB App Designer is used as the programming platform [Math19]. Figure 4-10 shows an overview of the platform, in which the *NC code and database-driven* approach is programmed as a simulation tool. The architecture and GUI of the simulation tool are described in the next subsection.

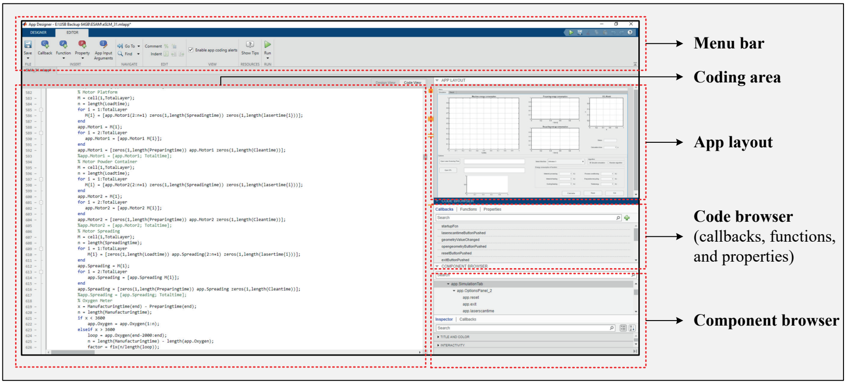



Figure 4-10: Overview of the development platform

## 4.5 Simulation tool

### 4.5.1 Architecture of the simulation tool

The architecture of the simulation tool can be illustrated in the form of a functional flow block diagram, as depicted in Figure 4-11. The first step is to import the *.stl* and *.lsr* files, from which the facet data of a component and the layer data of the build process are extracted, respectively. They are the second and third functions of the simulation tool. The facet data are used to visualize the geometry in the simulation tool, while the layer data are used to facilitate the energy simulation. It should be noted that the *.lsr* file only contains the time parameters for the build process belonging to the *in-step* phase. The time parameters for *pre-step* and *post-step* phases should also be defined. Following the simulation, the power curves of the AM machine and peripherals are visualized in the simulation, and the data can be exported in the form of *.txt* files.

The core function of the simulation tool is *energy simulation*, which features eight subfunctions. Followed by the third function *extract layer data*, the time parameters for the build process and the time parameters for phases *pre-step* and *post-step* are converted into a time array, as required by the *NC code and database-driven approach*. It should be mentioned that the sampling time should not be too short. For conventional manufacturing techniques such as milling or drilling, the sampling time for obtaining power values can be set to 0.1 s, as such processes only last for a few minutes or tens of minutes [Kara11]. However, for SLM, the build time can be up to hours or days, depending on the parameter set, part size, and system configuration. A shorter sampling time will lead to more frequent sampling and a massive volume of data. To avoid this, the sampling time for obtaining power values is defined as 1 s. After generating the time array, power values for each system component and point in time are generated based on the database and power adjustment function $f\,(P_t, A)$. Finally, after the integration of the power and time arrays, the energy values are calculated.

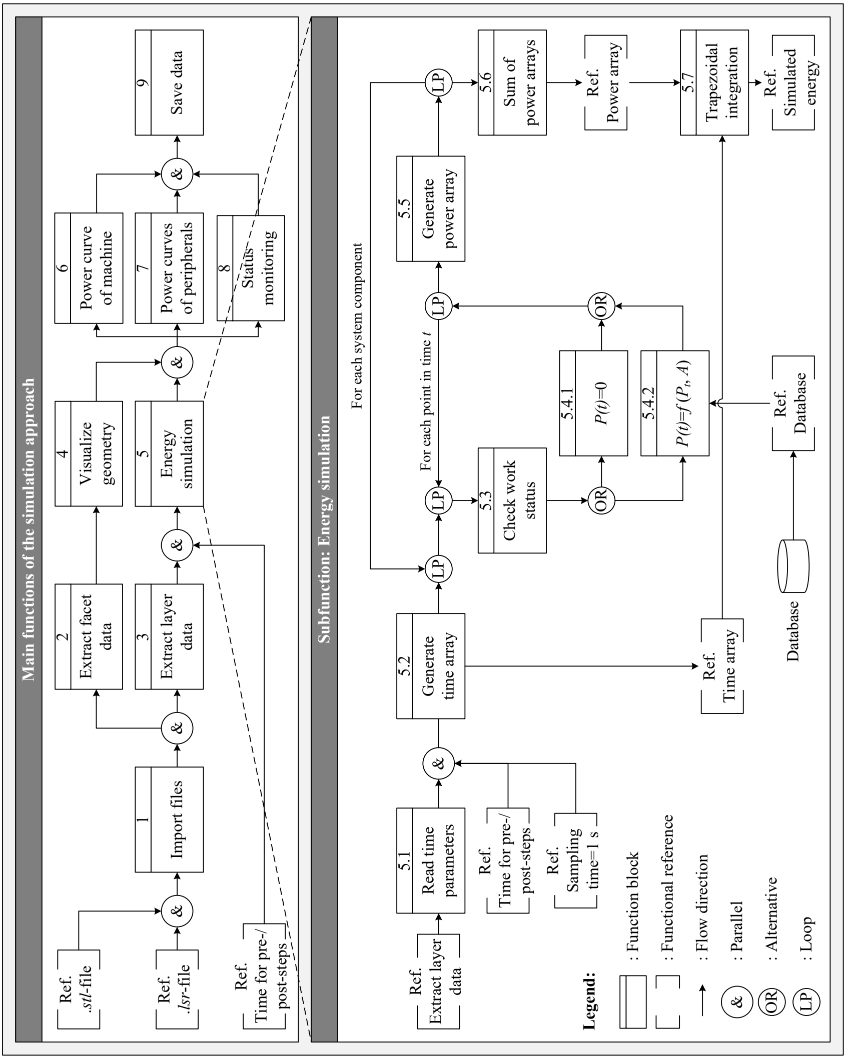



Figure 4-11: Functional flow block diagram of the simulation tool

### 4.5.2 GUI design

The GUI of the simulation tool is shown in Figure 4-12. Prior to the simulation, the *.lsr* and *.stl* files should be imported through the *file input bar*. During the simulation, the simulation status can be monitored and the *.stl* file can be visualized. After the simulation, the power curves of the *Concept Laser Mlab*, powder screen device, and vacuum cleaner are visualized, and the simulation data can be exported in the form of *.txt* file.

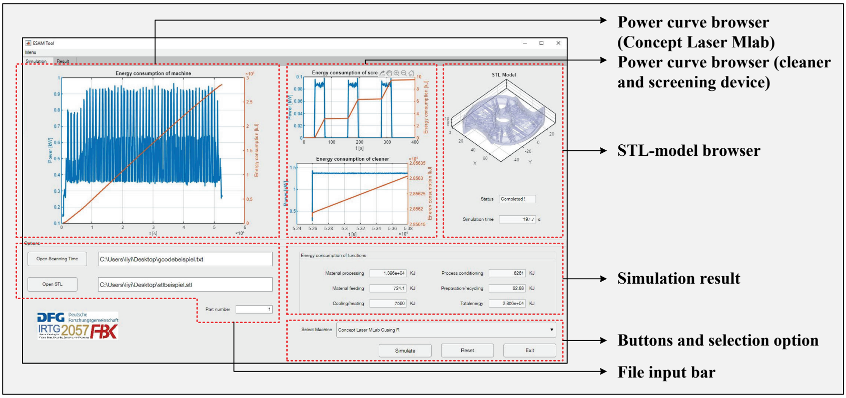



Figure 4-12: Overview of the GUI of the simulation tool

## 4.6 Experimental verification

### 4.6.1 Design and setup of experiments

The power meter used for the experiments is a *YOKOGAWA WT1806E* [Yoko19]. The wiring for the power measurement is depicted in Figure 4-13, in which the interfaces for measuring voltage are connected with the *Concept Laser Mlab* in parallel and the interfaces for measuring current are connected in series. In Figure 4-13, ① and ② are interfaces for measuring the voltage, while ③ and ④ are for measuring the current. During the measurement, a laptop captures the power data with a sampling time of 1 s. In the experiments, four build tasks with different components are performed. Thereafter, as is described in the next subsection, simulations of the build tasks are performed and the experimental data are compared.

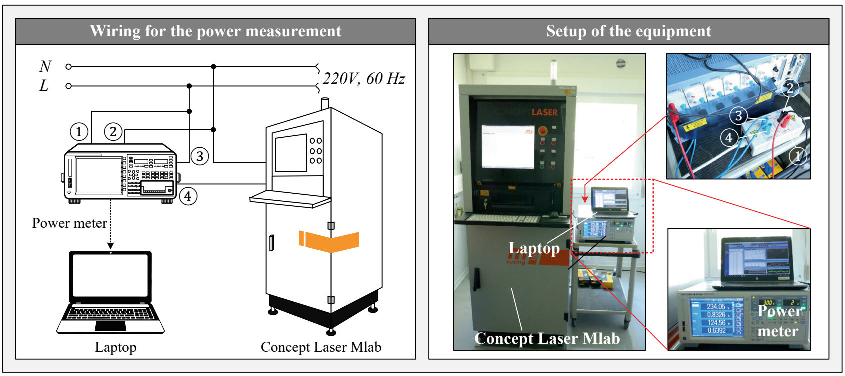



Figure 4-13: Overview of the setup used for the experiments

### 4.6.2 Comparison of experimental and simulation results

The analysis of the simulation accuracy begins with an evaluation of the power curves of the simulation and experiment. Figure 4-14 shows an exemplary power curve that is characterized by three stages. The first stage represents the calibration and vacuuming of the build chamber, the second stage indicates the build of layers, and the third stage indicates the cooldown. In the second stage, a periodic behavior is observed, as indicated by ④ and ⑤ in Figure 4-14A. The reason for this is that the cyclic operation of the cooling device's compressor leads to the cyclical power increasing by nearly 300 W. In addition, another periodical power increase is observed, as indicated by ⑥ and ⑦, which represent the laser scanning and powder spreading, respectively. During the laser scanning, the power use increases by nearly 210 W.

Although the simulated power curve and the actual power curve generally fit, there are still errors in the details. One obvious error is the time offset, which is indicated by ⑧. The reason for this error is that the time parameters used in the simulation are imported from *.lsr* file; these parameters differ from the actual time parameters. Thus, the timelines of the simulation and the experiment do not match.

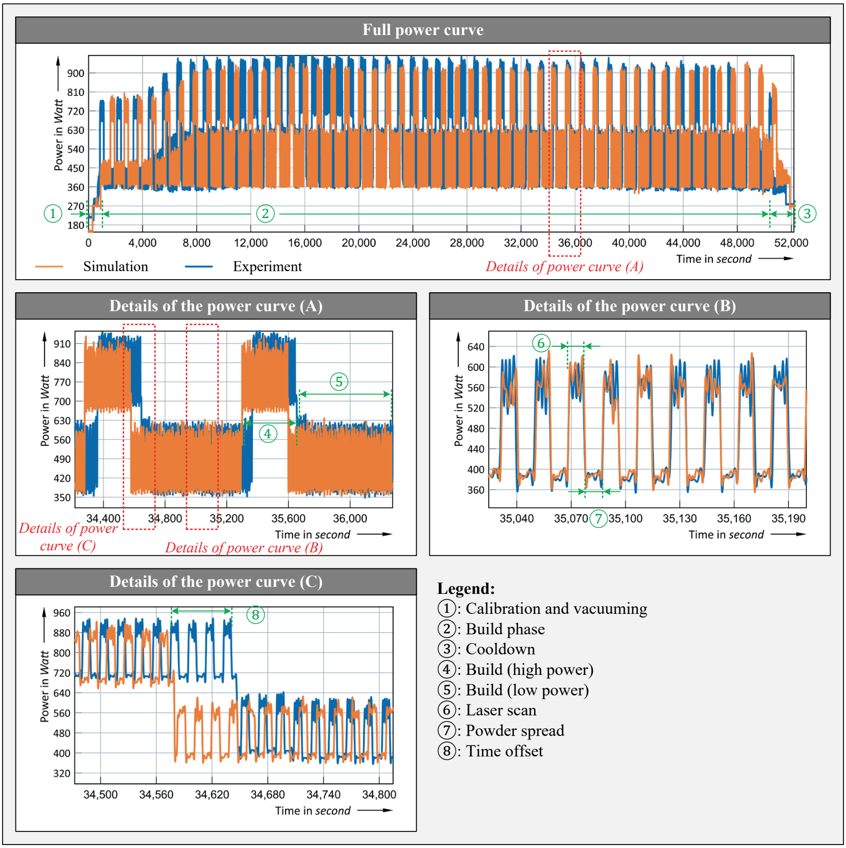



Figure 4-14: Comparison of simulated and experimental power curves

The deviation between the simulation and experiment is expressed in Equation 4-12, in which $P$ and $E$ represent the mean power and energy consumption, respectively:

$$\Delta P = |P_{exp} - P_{sim}|, \text{ and } \Delta E = |E_{exp} - E_{sim}| \qquad \text{Equation 4-12}$$

The simulation accuracies are further defined by Equation 4-13, in which $ACC_P$ and $ACC_E$ represent the accuracies for the mean power and energy consumption, respectively:

$$ACC_P = \left(1 - \frac{\Delta P}{P_{exp}}\right), \text{ and } ACC_E = \left(1 - \frac{\Delta E}{E_{exp}}\right) \qquad \text{Equation 4-13}$$

Table 4-3 summarizes the result of the simulation and experiments, including the calculated evaluation indicators. The highest and lowest $ACC_E$ and $ACC_P$ values appear in the first and second experiments, respectively. The mean $ACC_E$ and $ACC_P$ values for the four experiments are 96.43% and 96.19%, respectively. Since these values are both higher than 95%, it can be concluded that the simulation accuracy is verified and that the simulation tool can be used for the energy performance quantification and evaluation of the *Concept Laser Mlab*.

| No. | $n_{layer}$ | $t_{build}$ (min) | $P_{exp}$ (W) | $P_{sim}$ (W) | ΔP (W) | $ACC_P$ (%) | $E_{exp}$ (kWh) | $E_{sim}$ (kWh) | ΔE (kWh) | $ACC_E$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2546 | 874.48 | 554.51 | 546.16 | 8.35 | 98.49 | 8.03 | 7.91 | 0.12 | 98.51 |
| 2 | 433 | 181.15 | 467.79 | 493.86 | 26.07 | 94.43 | 1.41 | 1.48 | 0.07 | 95.04 |
| 3 | 605 | 153.00 | 428.14 | 445.53 | 17.39 | 95.94 | 1.10 | 1.14 | 0.04 | 96.36 |
| 4 | 1113 | 403.40 | 356.47 | 341.89 | 14.58 | 95.91 | 2.39 | 2.29 | 0.10 | 95.82 |

Table 4-3: Simulated and experimental results for the Concept Laser Mlab

Following the experiment, a simulation without the power adjustment function was conducted, and the impact on the simulation accuracy was not found to be significant. For example, for the first experiment, the total energy consumption for the simulation without the power adjustment function is 7.92 kWh, which is only 0.01 kWh higher than the simulation result with the power adjustment function (7.91 kWh from Table 4-3). This deviation is not significant and can be disregarded. Finally, the simulation accuracy of the screen device and the vacuum cleaner was also experimentally verified. For the screen device, the measured and simulated energy demands are 2.56 kJ and 2.62 kJ, respectively, and the simulation accuracy is 97.6%. For the vacuum cleaner, the experimental and simulated energy demands are 405 kJ and 408 kJ, respectively, leading to a simulation accuracy of 99.3%.

## 4.7 Discussion of the approach

### 4.7.1 Transfer of the development approach to FDM

To ensure the general feasibility of the developed approach for all AM processes, the approach has been applied to the FDM process. The reference FDM system is the *Ultimaker 3*; Figure 4-15 presents the technical data and photographs of this machine [Ulti19a]. The entire development approach, including system exploration, energy modeling, software implementation, and experimentation verification, was applied using this FDM system. The bond graph for the *Ultimaker 3* is provided in Appendix C. The NC code file for Ultimaker 3 is a *.gcode* file, which can be exported from the *Ultimaker Cura* software [Ulti19b]. Figure 4-15 shows the simulated and experimental power curves of the Ultimaker 3, which are characterized by five stages. During the first stage, standby, which is indicated by ① in Figure 4-15, the power consumption of the Ultimaker 3 is approximately 5 W; during the second stage (② in Figure 4-15), the platform is heated to 60 °C, and the power consumption increases to approximately 210 W. Thereafter, the print head and the print processes are calibrated during the third and fourth stages (③ and ④ in Figure 4-15), respectively. During the print process, the power consumption is approximately 130 W. Following the print process, the *Ultimaker 3* cools down, as indicated by ⑤ in Figure 4-15. The print process encompasses a cyclical behavior in which the leveling of the platform and extrusion of filaments cause a different level of power consumption, as indicated by ⑥ and ⑦ in Figure 4-15. Moreover, a time offset is also observed, in which the timeline from the NC code file varies from the real timeline, as indicated by ⑧ in Figure 4-15.

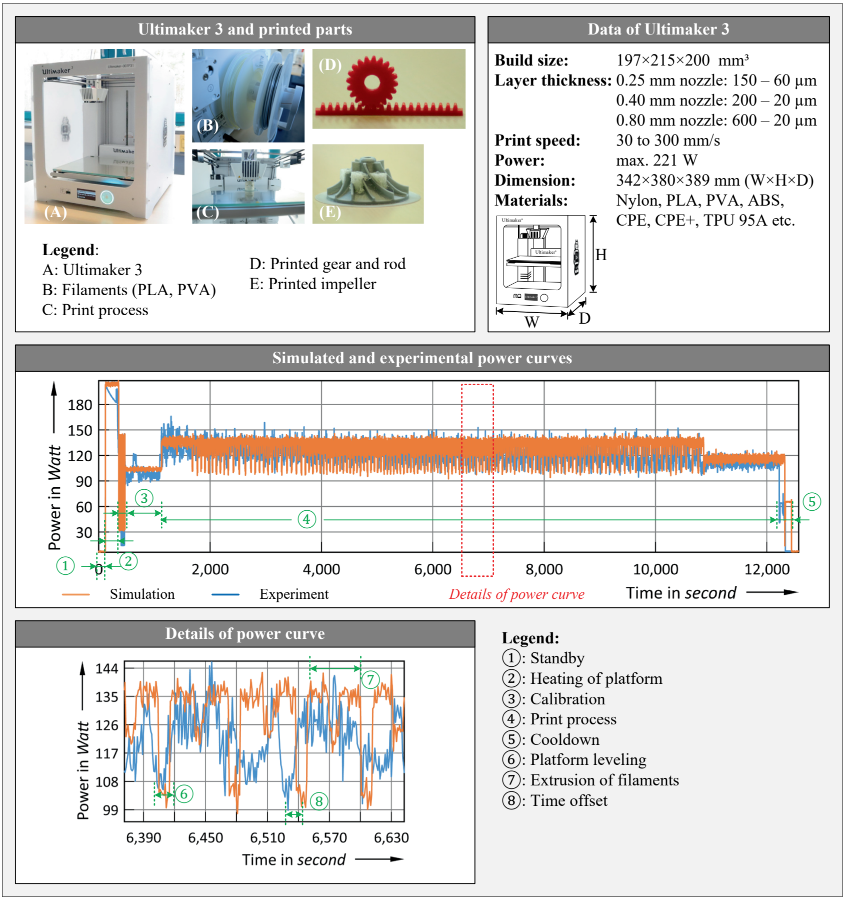



Figure 4-15: Development of the energy simulation for the Ultimaker 3

In the experimental verification, eight experiments were performed, the results of which are summarized in Table 4-4. The $ACC_E$ and $ACC_P$ values range from 90.5% to 98.4% and 95.4% to 98.5%, respectively, and the mean $ACC_E$ and $ACC_P$ values are 94.7% and 96.7%, respectively. Based on the transfer of the development approach to FDM, it can be concluded that the development approach presented in this dissertation, as well as the *NC code and database-driven approach,* demonstrates good feasibility for different AM processes.

| No. | $t_{build}$ (min) | $P_{exp}$ (W) | $P_{sim}$ (W) | ΔP (W) | $ACC_P$ (%) | $E_{exp}$ (kWh) | $E_{sim}$ (kWh) | ΔE (kWh) | $ACC_E$ (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 203.18 | 121.07 | 123.78 | 2.71 | 97.8 | 0.41 | 0.42 | 0.01 | 97.6 |
| 2 | 207.53 | 118.54 | 123.22 | 4.68 | 96.0 | 0.41 | 0.43 | 0.02 | 95.1 |
| 3 | 264.57 | 117.93 | 124.14 | 6.21 | 94.7 | 0.52 | 0.54 | 0.02 | 96.2 |
| 4 | 268.60 | 122.86 | 124.82 | 1.96 | 98.4 | 0.55 | 0.56 | 0.01 | 98.4 |
| 5 | 81.35 | 116.53 | 114.77 | 1.77 | 98.5 | 0.16 | 0.15 | 0.01 | 94.9 |
| 6 | 83.10 | 118.41 | 114.44 | 3.98 | 96.6 | 0.16 | 0.15 | 0.01 | 93.3 |
| 7 | 105.12 | 119.86 | 114.38 | 5.49 | 95.4 | 0.21 | 0.19 | 0.02 | 90.5 |
| 8 | 105.47 | 119.47 | 115.00 | 4.46 | 96.3 | 0.21 | 0.19 | 0.02 | 91.4 |

Table 4-4: Simulated and experimental results for the Ultimaker 3

### 4.7.2 Benefits and challenges of the simulation approach

Compared to existing approaches for the energy prediction of AM processes, the approach proposed in this dissertation offers the following innovative benefits:

- **Integration of NC code into the energy simulation**: In previous approaches related to the calculation of energy demands of AM processes, NC code was not considered. The main benefit of the proposed *NC code-driven simulation approach* is high prediction accuracy. Compared to energy prediction using the empirical method (e.g., the approach of BAUMERS ET AL. has the highest accuracy of 96.45%, [Baum13]), the accuracy in this approach can be up to 98.5%. The main reason for the improvement is the use of the time parameters from the NC code. Since the build process of AM is controlled by NC codes, the use of NC codes in the energy simulation implies a more detailed consideration of the process data, which eventually leads to increased accuracy.
- **Use of a power adjustment function to imitate real energy-consuming behavior**: An AM system is a complex mechatronic system comprised of both software and hardware. The power consumption of an AM system varies at each point in time of a build process and is influenced by machine and process parameters, the geometry of each layer of the object, and even ambient noise. If all these parameters are considered during the simulation, the complexity of the simulation model will be extremely high. Therefore, this approach simplifies the effects of these factors into a power adjustment equation based on adding or subtracting a randomly generated value according to an assumed constant. The benefit is that the simulated power curves more realistically indicate the energy-consuming behavior of an AM system.
- **Fast simulation through the use of a power database**: If the Simulink models are directly integrated into the GUI, the simulation time will be hours. The reason for this is that an AM build process can take hours or even days, and the simulation of system components that operate for hours or days in Simulink models is extremely time-consuming. Considering that a single AM machine comprises more than ten system components and Simulink models, the total GUI simulation time can be up to hours. However, by using a power database in which the simulation data of the Simulink models are already stored and having the GUI only takes power values from the power database, the simulation time can be reduced to seconds or minutes.
- **A greater understanding of the relationship between system and energy consumption**: The entire development approach adopts a function-oriented approach to system

exploration and energy modeling, which implies that the simulated energy consumption can be reassigned to the functions and components of the AM system. In contrast to previous empirical modeling approaches, in which an AM process is treated as a black box and the calculated energy consumption cannot be allocated to system components, this approach follows a white box principle and facilitates a deeper understanding of the relationship between the composition and the energy consumption of AM systems.

Despite the benefits described above, the approach developed in this dissertation is still subject to the following two challenges, which should be addressed prior to future implementation:

- **Time offset between the simulation and the real process:** The time parameters from the NC code and the actual process may be different. If the deviation between them is significant (e.g., the total process time in the NC code is 1 h, while the real process time is 1.5 h), the simulation result may not be reliable. For example, a machine that has just started up and a machine that has already performed several build tasks may require different times to heat up for a new next build task. Thus, even for the same build task, these machines' processing times may differ due to the time required for pre-heating. Unfortunately, the effects of the environment cannot be considered in an NC code. For the NC code-driven approach, the risk of time offset is always present. A solution to minimize this risk is to establish guidelines for standardizing tools, workflow, environment, and other factors during the application of AM processes to reduce the impact of the unpredictable factors that may affect the build time of an AM process.
- **Additional work required for the implementation of new AM systems:** Different AM systems feature different system compositions. Thus, when applying this approach to a new AM system, the entire process, starting from the system exploration stage, may have to be repeated. It is only for AM systems with the same or similar system architectures that the system exploration and energy modeling stages can be performed once, and the same Simulink models can be used again. For example, the Simulink models of the *Concept Laser Mlab* can be conveniently modified for other SLM machines with similar constructions. However, for AM systems system constructions that differ from those of SLM machines, all steps from the system exploration stage onward will have to be carried out. A solution to minimize the workload for the implementation of the developed approach may be that developers can create templates of Simulink models for AM systems falling in the same AM process category. The template Simulink models and parameters can then be modified for specific AM systems.

# 5 An Energy Performance Assessment Model for AM

This chapter describes the *multidimensional energy performance assessment model* for AM based on energy performance indicators (EnPIs). An EnPI is a metric of energy performance that refers to the measurable results associated with the energy efficiency, energy consumption, and energy use of a system or process [ISO14]. The model presented in this dissertation is divided into three levels: *original EnPI* (Level I), *normalized EnPI* (Level II), and *aggregated EnPI* (Level III). Chapter 5.1 provides an overview of the assessment model, while Chapter 5.2 describes the three levels in detail. Finally, Chapter 5.3 presents a discussion of the proposed assessment model.

## 5.1 Overview of the model

The quantification and assessment of energy performance for AM require a model capable of describing the specific implications of energy performance in the context of AM processes; in addition, this model should establish the basis for the calculation and assessment of the energy performance of AM-specific solutions in the eco-design. The proposed assessment model in this dissertation is adopted from an EnPI-based evaluation approach and is called the *multidimensional energy performance assessment model for AM*. This model consists of three levels, which are depicted in Figure 5-1.

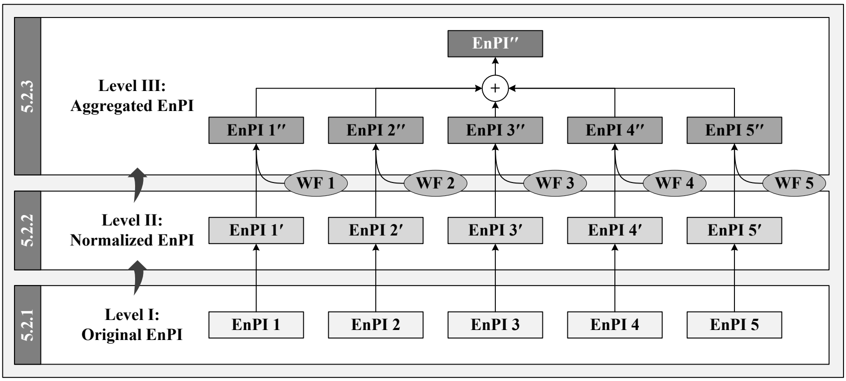



Figure 5-1: Overview of the multidimensional energy performance assessment model for AM

Level I features *original EnPI*s that can be directly investigated from AM processes. These EnPIs can be divided into four types: *direct energy values*, *ratios of energy values*, *combination of energy and non-energy values*, and *non-energy unit but related values*. The *original EnPI* level is introduced in Chapter 5.2.1. Since *original EnPIs* are expressed in different units and cannot be compared directly, they need to be normalized to eliminate their units so that they can be directly added to or subtracted from each other. Therefore, Level II is called *normalized EnPI*; this level is described in Chapter 5.2.2. In addition, in practice, users may have different expectations regarding different EnPIs, and the weighting factors for EnPIs may therefore need to be calculated based on the *pairwise comparison* approach. Thereafter, weighting factors (see WF in Figure 5-1) need to be multiplied by the normalized EnPI values; the results are called *aggregated EnPIs*, which comprise Level III. The sum of the *aggregated EnPIs* represents the final energy performance score of a design solution for AM, based on which different design solutions can be compared and the optimum solution can be selected (see Figure 5-2). The level of aggregated EnPIs is introduced in Chapter 5.2.3.

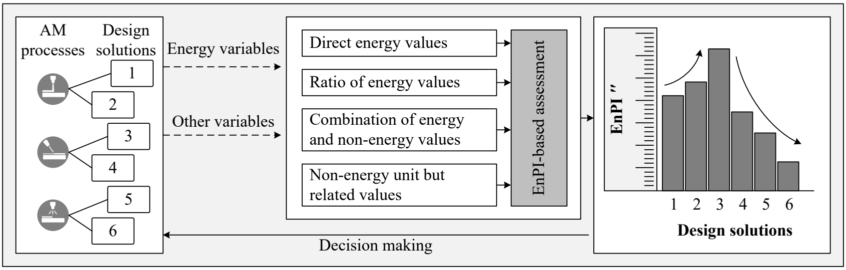



Figure 5-2: Concept of the EnPI-based approach to energy performance assessment

## 5.2 Description of the model

### 5.2.1 Level I: Original energy performance indicators (EnPIs)

In general, EnPIs should be defined individually by the designers who will perform an evaluation. In the model presented in this dissertation, the definition of EnPI is based on the composition of the energy and non-energy variables that can be directly investigated in an AM process. Based on the composition method and the resulting EnPI units, this dissertation identifies four types of EnPIs for AM: *direct energy values*, which describe the quantity of energy; *ratios of energy values*, which describe the division between the *direct energy values*; *combinations of energy and non-energy values*, which are derived from the combination of the *direct energy values* with other non-energy variables; and *non-energy unit but related values*, which are used directly or synthesized from the non-energy variables. Figure 5-3 shows the composition method and the four resulting EnPI types.

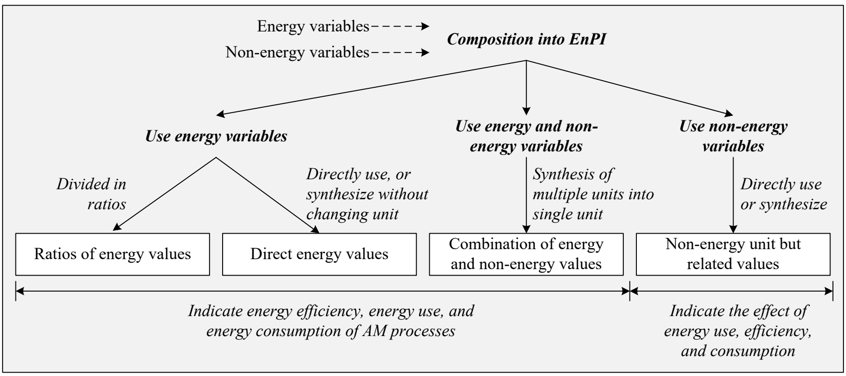



Figure 5-3: Classification of EnPI types

In AM, energy variables indicate the energy-related system or process properties (e.g., energy consumption), while non-energy variables imply non-energy properties (e.g., mass of a product). For defining EnPIs, designers have three fundamental composition methods: *use energy variables*, *use energy and non-energy variables*, and *use non-energy variables*. When only energy variables are used, there are two ways to compose EnPIs. First, energy variables can be used directly or synthesized without changing units (i.e., sum or minus). In this approach, the EnPIs are called *direct energy values* (e.g., energy consumption per build task, peak power, and the difference between the energy consumption of two AM systems). Second, energy variables can be divided into *ratios of energy values*, which indicate the energy transformation efficiency or exergy efficiency (e.g., the ratio between required and consumed energy demand or the ratio between the laser power and the total power of AM systems). For *combining energy and non-energy variables* into EnPIs, the units of both variables can be combined into single units. For example, the energy consumption of a build task in *joules* (energy variable) can be combined with the mass of a product in *kilograms* (non-energy variable) into specific energy consumption in *J/kg*. Finally, *non-energy variables* can be used by synthesizing them to create EnPIs. It should be noted that not every non-energy variable can be used as an EnPI; rather, only those that are energy-related can be used as EnPIs. While the *direct energy values*, *ratios of energy values*, and *combinations of energy and non-energy values* indicate the energy use, efficiency, and consumption of AM, *non-energy unit but related values* describe the effects of the energy use, efficiency, and consumption of AM (e.g., energy cost and residual stress).

In practice, EnPIs should be defined individually for different design purposes. Table 5-1 provides examples of EnPIs that developers can refer to for their own cases. In general, since *direct energy values* only consider energy or power values, they are suitable for design objectives that involve evaluating or optimizing the energy consumption or uses of different AM processes, product designs, or systems. If designers attempt to consider the energy efficiency or energy consumption of other design factors, such as products or AM systems, *ratios of energy values* and *combination of energy and non-energy values* would be more suitable. If designers attempt to consider the effects of the energy use of AM systems, such as thermal stress and displacement, *non-energy unit but related values* should be preferred.

| EnPI types | Examples of EnPI | Suitable design objectives |
|---|---|---|
| Direct energy values | Energy consumption per build task (J, kWh) | Evaluation and reduction of energy consumptions or uses for different AM processes, product design, etc. |
| | Energy consumption per day or week (J, kWh) | |
| | Energy waste in the build task (J, kWh) | |
| | Peak power consumption (W) | |
| Ratio of energy value | Ratio between required/consumed energy (%) | Evaluation and improvement of energy efficiency for different AM processes, machines, etc. |
| | Ratio between heat dissipation and energy consumption (%) | |
| | Ratio between laser power and total power (%) | |
| Combination of energy and non-energy values | Specific energy consumption (J/cm³ or J/kg) | Evaluation and improvements of energy use, consumption, or efficiency with consideration of other factors related to product, AM process, machines, etc. |
| | Energy consumption per layer (E/layer) | |
| | Ratio between power and print temperature (W/K) | |
| | Ratio between safety factor and energy consumption (1/J)* | |
| Non-energy unit but related values | Heat distortion (mm) | Evaluation and improvement of the effect related to the energy use of AM processes, machines, etc. |
| | Residual stress (MPa) | |
| | Energy cost (€) | |
| *: Safety factor describes the ratio between yield stress (MPa) and maximal stress (MPa) of a part, and hence, the unit of safety factor is MPa/MPa=1. | | |

Table 5-1: Examples of EnPIs and the design objectives for which they are suitable

### 5.2.2 Level II: Normalized EnPIs

In EnPI-based assessment, either single or multiple EnPIs can be used. Should designers attempt to use single EnPIs, the decision of an optimum design solution can be made based on comparing the EnPI values of all solutions. However, should designers adopt multiple EnPIs in an assessment, they may be confronted with the problem that different EnPIs indicate different optimum design solutions. For example, design solution A may consume less energy in total than solution B, while solution B may have a higher energy efficiency than A. Thus, since different metrics may indicate different optimum solutions, a final decision cannot be made. In addition, since different EnPI have different units, they cannot be added directly. To solve this problem, this dissertation applies the normalization method to eliminate the units of all EnPI and convert them into comparable units.

The normalization method used in this dissertation adopts the *min-max scaling approach*, which has been widely used for forms of data processing such as image retrieval [Akso01]. In this work, each EnPI's normalized value, denoted as $EnPI'$, can be scaled to a value belonging to the range [0,1]. The normalization can be performed based on either the maximum or the minimum value. The normalization of the EnPI value for $i$-th solution based on the minimum EnPI is expressed by Equation 5-1, in which max (*EnPI*) and min (*EnPI*) respectively represent the maximum and minimum values of all solutions:

$$EnPI_i' = \frac{EnPI_i - \min(EnPI)}{\max(EnPI) - \min(EnPI)} \qquad \text{Equation 5-1}$$

Similarly, the maximum EnPI value-based normalization is defined using Equation 5-2:

$$EnPI_i' = \frac{\max(EnPI) - EnPI_i}{\max(EnPI) - \min(EnPI)} \qquad \text{Equation 5-2}$$

The reason for proposing two normalization equations is that different EnPIs require different evaluation rules that in turn require different normalization strategies. For example, if the EnPI is the total energy consumption of an AM system, the general evaluation rule is that lower energy consumption implies greater energy-saving and should thus be considered a better rating (according to the principle "the lower, the better"). In this case, the maximum value-based normalization, as expressed by Equation 5-1, should be applied so that the minimum value will be normalized to "1," which is the highest value in the *min-max scaling approach*. However, if the EnPI is energy efficiency, the general evaluation rule for which is that a higher efficiency implies less energy waste and should be considered a better rating, the minimum value-based normalization according to Equation 5-2 should be used (according to the principle "the higher, the better"). Hence, the maximum energy efficiency will be normalized to the value "1." In the assessment model proposed in this dissertation, the normalization of an EnPI can be based on either the maximum or the minimum value, but not both simultaneously.

Figure 5-4 shows an example of the normalization of an EnPI for four solutions. The normalization of the EnPI can be performed based on Equation 5-1 or Equation 5-2. In the case of the maximum value-based normalization, the EnPI value for solution A is normalized to "0," while the EnPI value for solution D is normalized to "1." In the case of the minimum value-based normalization, the results for solutions A and D are reversed such that the normalized EnPI value for solution A is "1," while the normalized EnPI value for solution D is "0."

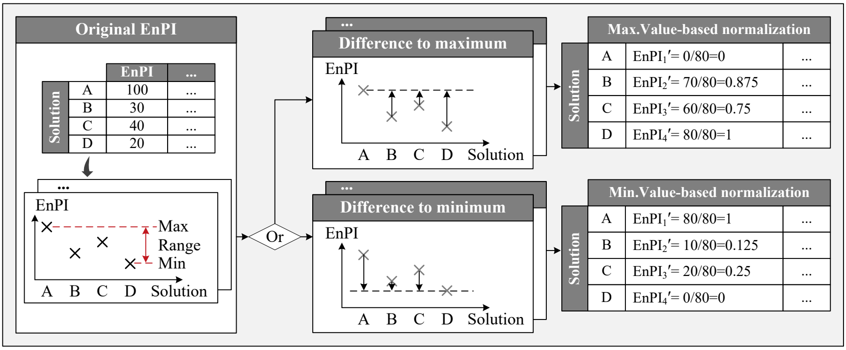



Figure 5-4: Normalization of an EnPI

### 5.2.3 Level III: Aggregated EnPIs

In general, different normalized EnPIs can be added to or subtracted from each other to obtain a final value representing the energy performance of a particular design solution. However, regarding different EnPIs, priorities with regard to EnPIs should be determined, according to which the EnPI weighting factors should be calculated and integrated with normalized EnPIs. For weighting EnPIs, the *pairwise comparison approach* is applied, in which each EnPI is compared two-by-two with all other EnPIs. The weighting factor of each EnPI is calculated based on its priority in the comparison. Figure 5-5 depicts an example in which five different EnPIs are assumed. Before the *pairwise comparison* is applied, the priority of each EnPI should be defined by a designer. During the *pairwise comparison*, the EnPI in each row is compared to the EnPIs in the other columns. If the priority of the EnPI in the row is higher than, equal to, or lower than the priority of the EnPI in a column, the values of 6, 3, and 1 should be assigned to the corresponding fields of the matrix, as depicted in Figure 5-5.

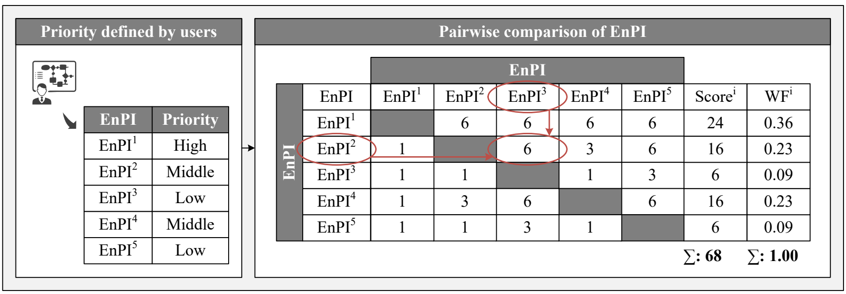



Figure 5-5: Prioritization and weighting of EnPIs

The final score of the *j*-th EnPI ($EnPI^j$) is the sum of the values assigned to this EnPI, and its weighting factor ($WF^j$) is the ratio of its score to the sum of the scores of all EnPIs, as expressed by Equation 5-3:

$$WF^j = \frac{Score^j}{\sum_{m=1}^{k} Score^m} \qquad \text{Equation 5-3}$$

After the weighting of EnPIs, the normalized EnPIs are aggregated with their respective WFs. For the *i*-th design solution and *j*-th EnPI, the product of the normalized EnPI (denoted as $EnPI_i^{j}{}'$) and the $WF^j$ is the aggregated $EnPI_i^{j}{}''$, as expressed by Equation 5-4:

$$EnPI_i^{j''} = EnPI_i^{j'} \times WF^j \qquad \text{Equation 5-4}$$

Figure 5-6 shows an example of the aggregation of EnPIs, in which five EnPIs are assumed. For a design solution (denoted as solution A, in which *i* takes the value of 1), the values for the original EnPI are normalized and aggregated with their WFs. The final energy performance score of the design solution ($EnPI_i''$) is the sum of all aggregated EnPIs ($EnPI_i^{j}{}''$), which is determined using Equation 5-5:

$$EnPI_i'' = \sum_{j=1}^{k} EnPI_i{}^{j''} \qquad \text{Equation 5-5}$$

The final energy performance score represents the final energy performance of a design solution. The best design solution can be selected by comparing the final energy performance score, with the highest score indicating the optimum design solution.

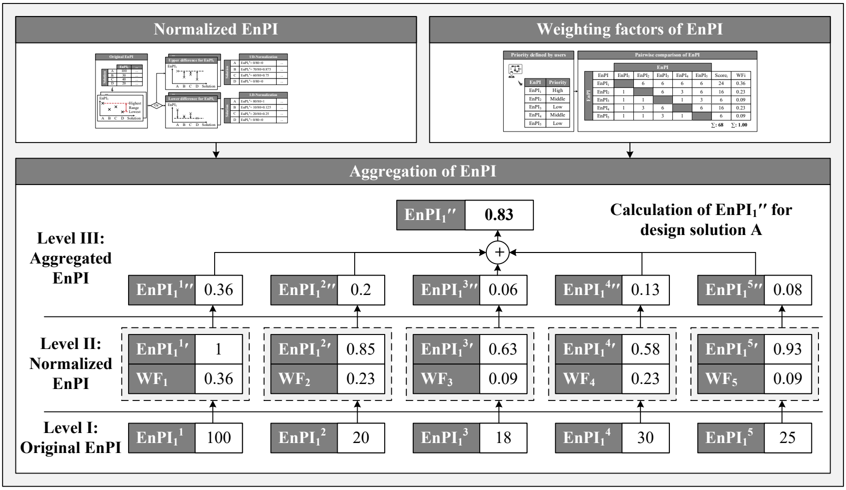



Figure 5-6: Aggregation of normalized EnPIs with weighting factors

## 5.3 Discussion of the model

The model proposed in this dissertation describes the energy performance of an AM process and is divided into three levels. The assessment model is the core element of the eco-design for AM method presented in this dissertation, which is introduced in Chapter 6. Compared to existing approaches, the model presented in this dissertation offers the following benefits:

- **Enabling assessments based on multiple EnPIs**: In existing approaches, the energy performance of AM is always evaluated based on a single indicator (e.g., total energy consumption or specific energy consumption). Through the use of the normalization technique, the proposed model enables the definition, calculation, and evaluation of multiple EnPIs. The application of multiple EnPI-based assessment further enables a more comprehensive consideration of the energy performance of an AM process.

- **Consideration of non-energy variables.** In existing approaches, assessment of the energy performance of AM processes mainly focus on energy variables and neglect non-energy variables. The most used EnPIs are total energy consumption, specific energy consumption, and adiabatic efficiency (e.g., [Lune20, Guto17, Kell17]). The model proposed in this dissertation allows for combining non-energy variables together with energy variables, meaning that the process characteristics and design benefits of AM are also considered in assessments.
- **Integration of subjective design needs**. Energy consumption is a metric that can be quantified using objective means such as experiments or simulations, and it is independent of the subjective expectations of designers. In the proposed model, the weighting factors of EnPI are multiplied by the normalized EnPI. Since the weighting factors are derived from the *pairwise comparison* based on priorities that are pre-defined by designers, the integration of the weighting factors with EnPIs also implies the consideration of the subjective expectations of designers in the assessment. The benefit is that the selected optimum solution will be closer to the design requirements as well as the designer's application scenario.

Beyond the advantages described above, the implementation of the proposed *multidimensional energy performance assessment model* faces a challenge in that the use of multiple EnPIs also implies a high complexity of calculation and the additional effort of investigating the non-energy variables. A solution to this challenge could be the use of computer-aided engineering (CAE) software to simulate the characteristics of the AM process for a given AM system and process parameters.

# 6 An Eco-Design for AM Method

This chapter describes the method of eco-design for AM, in which the proposed simulation tool and assessment model are applied. The method is presented in the form of a process model consisting of five phases: situation analysis, topology optimization, AM workstation design, build process design, and EnPI-based assessment. Chapter 6.1 provides an overview of the method, and the details of each phase are introduced in Chapters 6.2 to 6.8. Finally, Chapter 6.9 presents a discussion of the proposed method.

## 6.1 Overview of the method

The fundamental logic of the proposed eco-design for AM method is to propose different design solutions by varying the parameters in designing products, systems, and processes with AM and to then use the *multidimensional energy performance assessment model* to select the optimal design. Based on the developed simulation tool and assessment model, the eco-design for AM method based on energy performance quantification and assessment is presented in the form of a general process model with five phases, which is depicted in Figure 6-1.

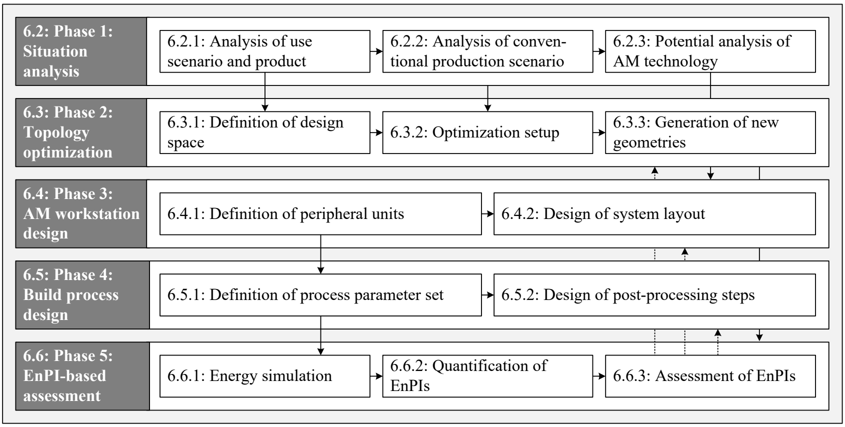



Figure 6-1: Overview of the proposed eco-design for AM method

The first phase aims to analyze the initial situation of a design case, in which the geometric features and functions of a product, the use condition for that product, and the conventional production scenario are analyzed. In addition, the AM process that should be considered during the design is also specified and evaluated with regard to its technical and economic aspects in this phase. In the second phase, the product should be designed based on the initial situation and design requirements; in this process, topology optimization is applied to create new product geometries based on the defined functional surfaces and constraints. Topology optimization is an iterative process in which FEA is used to evaluate the performance of geometries under certain mechanical conditions and the volumes with less impact on the performance of the AM process are removed. The purpose of topology optimization is to propose different product geometries for developing multiple design solutions. The third phase involves designing an AM workstation to carry out the build task of the designed product. During the process of designing the AM workstation, an AM machine and its peripheral units are selected and the layout thereof is planned. Similarly to the topology optimization process, different AM machines can be considered in the process of designing the AM workstation to develop different design solutions. Thereafter, in the fourth phase, namely the build process design phase, the process parameters of the build, such as layer thickness and laser speed, are defined. It should be noted that the material properties of AM parts, such as porosity and fatigue, are sensitive to the process parameters; thus, process performance should be considered while designing process parameters. In this method, the evaluation of the process performance is performed using thermal-structural simulations. Moreover, during the process design stage, multiple parameter combinations can also be proposed. Finally, different product geometries, AM workstation designs, and build process parameter combinations yield different design solutions, which are considered during the fifth phase. In the fifth phase, the energy simulations for all design solutions are performed, and the EnPIs for each design solution are calculated, normalized, weighted, and aggregated into the final energy performance score, according to which the optimal design solution is selected.

An example in the form of a design in which a holder block is used as a reference component is used throughout the description of the eco-design for AM method. The holder block is part of the equipment to measure the scratch process of an indenter with a diamond abrasive tool, as depicted in Figure 6-2. The indenter can be inserted into the holder, which is then fixed on a bracket, and a servo drives a glass pane to execute the scratch process. The result of the scratch is compared with the result of an FE model to characterize the properties of the abrasive manufacturing process. The holder has eight holes and is a solid part without further complex geometrical features; the following subsections present the details of the design example.

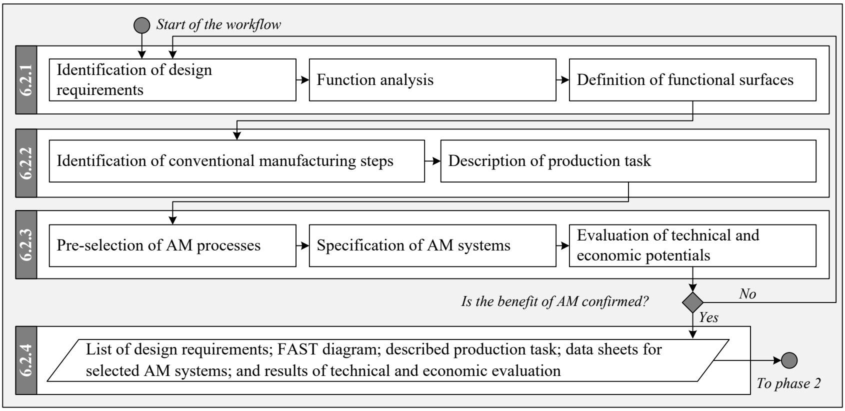



Figure 6-2: Example of a holder design

## 6.2 Phase 1: Situation analysis

In the situation analysis, a product and its use condition are first specified, in which general design requirements are defined according to the use scenarios of customers and the functions of the product are modeled using a function analysis system technique (FAST) approach. Thereafter, the manufacturing steps and production tasks in a conventional production scenario are specified. Based on the desired product function and specified production scenario, AM processes and systems with application potentials are analyzed and evaluated with regard to their technical and economic aspects. Therefore, the workflow of this phase comprises three tasks: analysis of use scenario and product, analysis of conventional production scenario, and potential analysis of AM technology. The following subsections describe the phases, and Figure 6-3 depicts the subtasks in each phase.

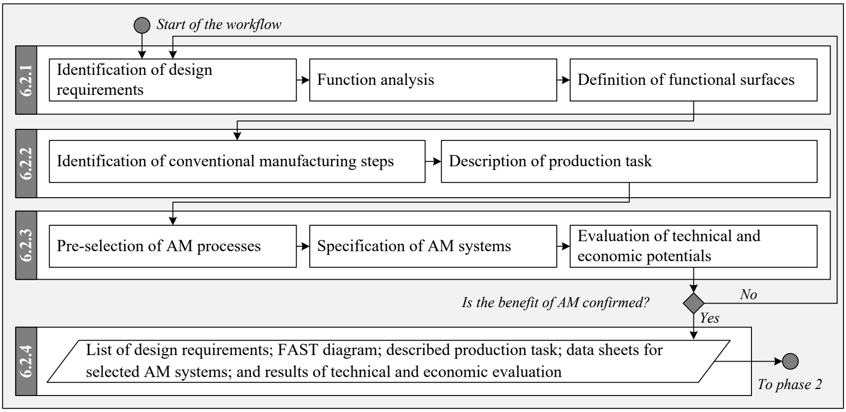



Figure 6-3: Overview of the situation analysis

### 6.2.1 Analysis of use scenario and product

The use scenario for a design case represents a boundary condition that a designer should consider during the design process. The analysis of the use condition and product consists of three subtasks: identification of design requirements, function analysis, and definition of functional surfaces.

#### Identification of design requirements

Design requirements describe the physical or functional conditions that a specific product or process design should fulfill and can be proposed by either internal (manufacturer) or external (customer) fields. This dissertation identifies the following four types of design requirements:

- **Product-related requirements**: This category summarizes requirements related to the desired properties of a product. Such requirements include those concerning specific materials, shape, function, aesthetics, use purpose, and quality.
- **Production-related requirements**: These requirements refer to the desired properties of the production system and process chain used to produce the designed product. Such requirements include those concerning the flexibility of the production system, the reliability and stability of the production process, and the cycle time of production.
- **Customer-related requirements**: These requirements are related to the customer use scenarios in which the designed product will be applied. Therefore, based on the individual use purposes, customers may have requirements in terms of delivery time, quality, or cost.
- **Regulatory-related requirements**: This category consists of requirements related to the national or international legal frameworks that a designer should obey. These frameworks can include standards for production safety, quality, environments or other specific regulations.

The definition of these requirements can be carried out in the form of a workshop in which designers, production staff, and customers can participate. The outcome of the workshop is a list of design requirements that establish the boundary conditions for further design and assessment activities. Figure 6-4 shows the list of requirements for designing the example holder, in which eight requirements are defined based on the workshop held with the researchers who performed the scratch experiment and applied the holder. During the experiment, the scratch process will exert a vertical force on the indenter. Since the indenter will be fixed on the holder, a vertical force of up to 300 N can be applied to the holder. Therefore, the main requirement for the design case is that the designed holder must withstand a load of 300 N.

| No. | Type | Description of the requirement |
|---|---|---|
| 1. | Product-related requirements | The holder must ensure that the position of the indenter can be adjusted in the vertical direction. |
| 2. | | During experiments, the maximum vertical force applied to the indenter can be up to 300 N, and hence, the holder should withstand a load of 300 N at least. |
| 3. | | Since the scratch process can be influenced by the pressure angle of the indenter, the holder should enable the change of the pressure angle of the indenter. |
| 4. | | At least 50% weight reduction is expected during the product optimization while ensuring that experimental needs are satisfied. |
| 5. | Production-related requirements | The production process should be able to produce the holder with desired quality. |
| 6. | | Use as less energy and material as possible while ensuring that experimental needs are satisfied. |
| 7. | Customer-related requirements | The design and production have to be completed as soon as possible due to the impending launch of experiments. |
| 8. | Regulatory-related requirements | Consideration of the standards for geometrical product specifications (ISO 17450-2), environmental evaluation of machine tools (ISO 14955-1), energy performance assessment (ISO 50006). |

Figure 6-4: List of requirements for the design example of the holder

### Function analysis

After the design requirements are collected, the functions of the product should be defined. For this step, a FAST in which the functions of a product are described according to their logical relationships is applied [Mukh18]. Figure 6-5 shows the FAST diagram of the holder used as the design example.

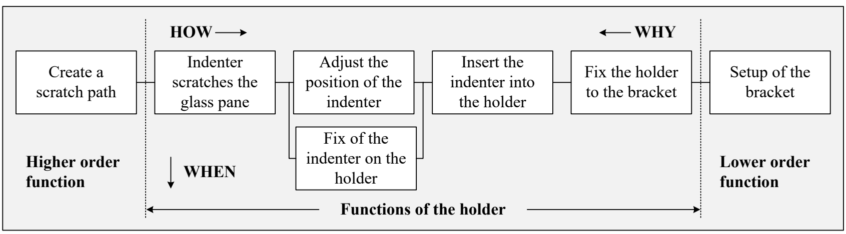



Figure 6-5: Function analysis system technique (FAST) diagram of the holder

In analyzing functions using a FAST approach, the first step is to determine which functions have lower and higher orders, respectively. For the holder, the higher-order function is *Create a scratch path* (output), while the lower order function is *Setup of the bracket* (input). Therefore, the functions of the holder describe a sequence in which the gap between its higher and lower order functions is bridged.

In the second step of a FAST approach, the functions should be described from left to right following a *HOW* principle, which involves considering the following question: *How is the function achieved?* For example, to enable the function *Create a scratch path*, the indenter with an abrasive tool should scratch the glass pane. Therefore, the function *Indenter scratches the glass pane* is defined on the right side of the function *Create a scratch path*, as depicted in Figure 6-5. Subsequently, to enable the function *Indenter scratches the glass pane*, the indenter should first be fixed on the holder at an appropriate angle. Therefore, the functions *Adjustment of the position of the indenter* and *Fix of the indenter on the holder* are described to the right side of the *Indenter scratches the glass pane* function. Moreover, since the functions *Adjustment of the position of the indenter* and *Fix of the indenter on the holder* should be performed simultaneously, their description follows a *WHEN* principle, which involves asking the following question: *When performing this function, what other functions should be executed simultaneously*? Subsequently, before the position of the indenter is adjusted, the indenter has to be inserted into the holder and the holder has to be fixed on the bracket. Therefore, the functions *Insert the indenter into the holder* and *Fix the holder on the bracket* are further described. Thereafter, the lower order function *Setup of the bracket* is performed and is directly connected to the *Fix the holder on the bracket* function.

The final step of the FAST approach is to review the modeled functions from right to left following a *WHY* principle, which involves considering the following question: *Why is this function necessary*? For example, for checking the functions of the holder, the logical reasoning may be as follows: *The bracket has to be set up, as the holder will be fixed on it. Fixing the holder on the bracket is necessary, as, otherwise, the indenter cannot be inserted into the holder. The indenter needs to be inserted into the holder because the indenter should be fixed on the holder at an appropriate angle. The indenter has to be adjusted and fixed because the indenter will scratch the glass pane to create a scratch path for a scratch experiment*.

In practice, FAST can also be implemented by first adopting the *WHY* principle and then the *HOW* principle to check functions or by applying the *HOW* and *WHY* principles simultaneously. The FAST approach is a convenient and flexible tool for function analysis, and the most important rule for its implementation is that the functions described in a FAST approach should be causally linked to each other.

**Definition of functional surfaces**

The final task in the analysis of the use condition and product is the definition of the functional surfaces of a product. A functional surface refers to a surface created by a manufacturing process; the term functional surface refers to the outer boundary of an object that isolates that object from the surrounding environment [Lona02]. While functions are generally described and not specific to a product, functional surfaces describe the physical attributes associated with specific products. Therefore, the definition of functional surfaces implies the transformation of conceptual and neutral functions into the specific physical geometrical features of a product.

In the design example of the holder, the functional surfaces are the holes shown in Figure 6-2. The collaboration between the functional surfaces and the functions of the holder is depicted in Figure 6-6, in which holes 1 and 2 are intended to be used to connect the holder with the bracket by inserting two screws and the indenter can be inserted into either hole 6, 7, or 8 in order to vary the pressure angle as required by the experiment. Finally, by adjusting the position of the indenter, a screw can be inserted into thread hole 3, 4, or 5 in order to attach the indenter to the holder. Described in the top half of Figure 6-2 are the five functions of the holder that have been defined based on the FAST approach, while the functional surfaces and the physical body of the holder are described in the bottom half of Figure 6-2. Moreover, it should be noted that the design example of the holder represents a case in which an existing product is redesigned, in which the functional surfaces can be directly described based on the existing product. In practice, there may be cases that involve designing new products; in such cases, the functional surfaces should also be determined according to their defined functions.

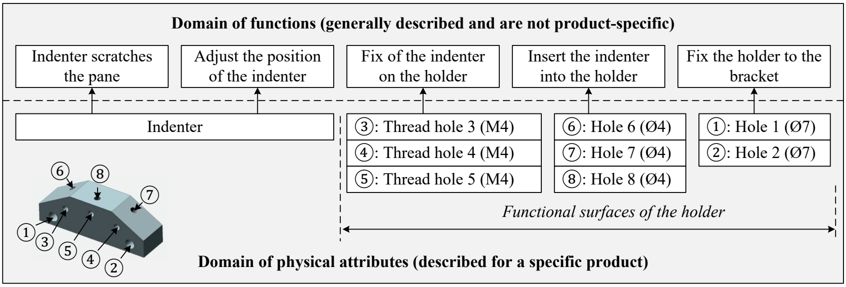



Figure 6-6: Relationship between the functions and the functional surfaces of the holder

### 6.2.2 Analysis of conventional production scenario

While the analysis of the use condition implies an investigation of the initial situation from the user's perspective, the analysis of conventional production scenario involves the clarification of the initial situation from the producer's side. The latter analysis encompasses two subtasks: identification of conventional manufacturing steps and description of production task.

**Identification of conventional manufacturing steps**

In conventional methods, the manufacturing steps of a product are defined according to its geometrical and functional properties [Kloc07]. In terms of the design case, the manufacturing process chain is defined according to the contours and functional surfaces of the holder. Figure 6-7 shows the process chain, in which four manufacturing steps are described. In a conventional scenario, a rectangular raw material is used to produce the holder. The first step of the process chain is to create the outer contour of the holder by means of a milling process. Thereafter, the second and third steps involve drilling holes 1 and 2, each of which has a diameter of 7 mm, and holes 6, 7, and 8, each of which has a diameter of 4 mm. In the final thread drilling step for holes 3, 4, and 5, three through holes with a diameter of 3.3 mm are first made and then the M4 thread holes are created.

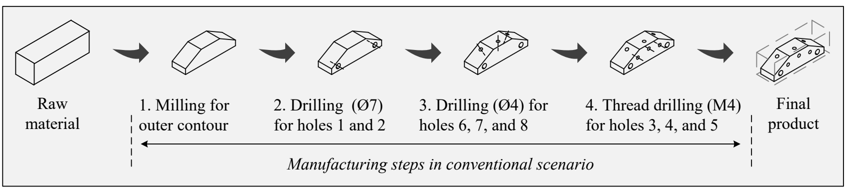



Figure 6-7: Identification of the manufacturing steps of the holder

**Description of production task**

After a product is analyzed and the manufacturing steps are identified, the production task associated with that product can be described, in which four dimensions of information should be considered (see Figure 6-8 [Ever96]). The first dimension is called *order details*; it includes information such as the product name, customer, series size, and other important information related to a customer order. The second dimension, *geometry*, comprises information concerning the geometrical properties of a product (e.g., size, volume, and number of surfaces, holes, or other form elements). The third dimension is *manufacturing technology*, which summarizes the information related to the manufacturing process chain, such as the number of manufacturing steps, the material used, and any requirements in terms of geometrical accuracy or surface finishing. The final dimension is called *time information*, which includes information concerning time parameters for manufacturing, logistics, tool preparation, and other operations related to manufacturing steps.

In terms of the design case, most information was already collected during the previous step. For example, the order information was specified during the analysis of the use scenario, while the geometry of the holder was analyzed during the definition of the functional surfaces.

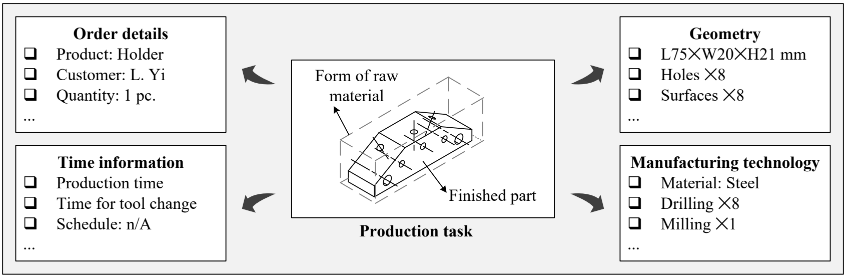



Figure 6-8: Description of the production task of the holder

### 6.2.3 Potential analysis of AM technology

After analyzing the conventional production scenario, the potential of AM in comparison to that of conventional manufacturing should be analyzed and identified. In particular, as the final step of the situation analysis, before performing further design and assessment activities, it should be confirmed whether an AM technology is necessary and whether it is capable of substituting the conventional production scenario for a specific product. In this step, the potential of AM on the machine level is regarded from a technical and an economic perspective. Therefore, the analysis of the potential of AM is executed in three steps: pre-selection of AM processes, specification of AM systems, and evaluation of technical and economic potentials.

**Pre-selection of AM processes**

The first step of the potential analysis is to perform a preliminary selection of AM processes and to decide which AM processes could be considered in further design and evaluation activities. For the pre-selection, the following criteria are considered:

- ❑ **Build size and speed**: Build size is an important factor in determining whether an AM process should be included or excluded in a design case, as the volume of a component should not exceed the maximum build size of an AM system. Therefore, sizes of machines available on the market for AM processes should be considered. In addition, the build rate also has a significant impact on processing time and product quality. The build times of AM processes can vary from hours to days depending on the process parameters and configuration of AM systems. Therefore, a higher build rate implies a rapid completion of build tasks and higher productivity.

- **Processable material**: In general, the more material an AM process can process, the greater potential it has, since it can perform more diverse production tasks. Particularly when a specific material is explicitly required for a case, determining whether an AM process is capable of processing that material is a decisive factor in determining whether that AM process should be considered.
- **Technical capability**: The most important quality features of AM products are *surface quality*, *geometrical accuracy*, *porosity*, and the *mechanical properties* of the produced components [Schm17]. Therefore, in the pre-selection process, one should consider the technical capabilities of an AM process, such as the capability of achieving the minimum desired wall thickness, the material density and surface finish that can be achieved, the strength of the manufactured part, and dimensional accuracy.
- **Support by manufacturer**: Since design for AM requires AM-related knowledge, users may need support from AM technology providers while designing their products. Means of providing such support include, but are not limited to, offering technical documentation, making manufacturer or service partner hotlines available, and providing consulting services and training. Support is important to take into consideration during the pre-selection stage, as a wider range of support options implies that an AM process has a higher potential.
- **Investment cost**: The AM equipment and materials available on the market for different AM processes are priced at different levels. The additional costs associated with providing staff training and reorganizing production networks can make investing in AM process extremely costly. In the pre-selection stage, investment costs can be a decisive factor, especially for small and medium-sized companies, which tend to be sensitive to cost factors.
- **Data availability**: The availability of data regarding AM process and system is an important factor in the pre-selection stage, as large amounts of data are required to calculate EnPIs. In addition to technical and cost data, the availability of energy-related data such as power consumption should be considered. In general, the more data that can be found for an AM process, the greater the potential that AM process may have.

Based on the evaluation of the six criteria, it can be decided whether to include or exclude an AM process during the design stage. For the design example, SLM is pre-selected as the AM process to be studied in further design and assessment activities, as it is one of the most widely applied AM processes for metal parts. Nevertheless, the evaluation in this step can be further detailed to the machine level, as is described in the next subsection.

**Specification of AM systems**

It is necessary to identify one or more AM systems that have potential in terms of the pre-selected AM process(es) required in a design case. For each AM system, a datasheet containing important data on that system is created; this datasheet will be used in the following technical and economic evaluations. In a datasheet, the collected data concerning an AM system can be summarized in three categories: *general data*, which refer to the information provided by the manufacturer; *technical data*, which refer to the information concerning the manufacturing capabilities of AM systems; and *cost data*, which refer to information related to the time and cost of AM systems. For the specification as well as the data collection, the relevant data sources include, but are not limited to, scientific articles, reports, feedback from commercial consulting, and product sheets provided by manufacturers.

Figure 6-9 shows the datasheet of the Concept Laser Mlab SLM machine, in which the data are collected from *Wohlers Report 2019* and the product documents provided by the manufacturer [Conc19a, Wohl19].

| Data sheet of AM systems | |
|---|---|
| **General data** | |
| System manufacturer | GE Additive Concept Laser |
| Machine type | Concept Laser Mlab Cusing |
| Process category | Powder bed fusion (Selective laser melting) |
| **Technical data** | |
| Build volume | x-y in 50✕50, 70✕70, or 90✕90 mm²; z=80 mm |
| Layer thickness | 15 to 50 µm |
| Laser source | Fibre laser 100 W (cw); focus diameter is approx. 50 µm |
| Processible materials | Aluminum alloy, stainless steel 316L, stainless steel 17-4PH, bronze CuSn, titanium alloy, cobalt-chromium alloy, silver, gold, platinum |
| Achieved density after build | > 99.5% |
| Accuracy from CAD to part | ± 0.05 |
| Geometric limitation | Minimum wall thickness from 0.1 to 0.2 mm |
| Surface finish (Ra) | 4.5 to 7 µm |
| Build rate | 1 to 5 cm³/h |
| Operations related to the build process | Preparation of CAD model and *.stl*-file, definition of process parameters, powder screening and loading, powder recycling, removal of support strucutre, and post-processing |
| **Cost data** | |
| Purchase price | Basic price 163,000 € |
| Cost factors | Machine cost, material cost, electricity cost, labor cost, cost for protection gas |
| Datum: May. 2019 | Created by: L. Yi |

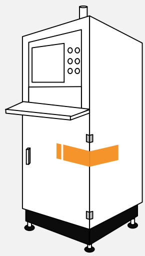


Figure 6-9: Datasheet of the Concept Laser Mlab SLM system

### Evaluation of technical and economic potentials

In the final step of the potential analysis, the selected AM systems are evaluated with regard to their technical and economic dimensions. Compared to the evaluation in the pre-selection, in which AM processes are generally and roughly assessed, the technical and economic evaluations should be performed for specific products. From a technical perspective, when deciding to include an AM system in a design case, it should have at least one of the following benefits when compared to conventional manufacturing:

- ❑ **Reduction of manufacturing steps**: For a given AM system, it is necessary to determine whether the number of manufacturing steps for a specific product in the AM scenario will be reduced in comparison with the conventional production scenario. To assess this criterion, the information in the datasheet concerning the pre- and post-operation should be considered.

- **Enhanced product quality**: Compared to the conventional production scenario, an AM system should provide superior or at least equivalent product quality. For assessing this criterion, technical data such as the achieved density, surface finish, and accuracy from CAD to part in the datasheet should be considered with regard to the production requirements of a specific product.
- **Manufacturability of complex geometries**: An important advantage of AM over conventional manufacturing is the feasibility of creating complex geometries such as lattices and hollow bodies. Therefore, a selected AM system should be capable of processing the complex geometrical features of a specific product. For assessing this criterion, technical data concerning geometrical limitations, layer thickness, and accuracy from CAD to part are considered with regard to the geometrical features of a specific product.
- **Increased productivity and flexibility**: In general, modern production systems tend to deal with production tasks characterized by a higher level of quantity and variety. Therefore, a selected AM system should enable the improvement of the productivity and flexibility of production systems. For assessing this criterion, the build volume and build rate in the datasheet should be considered with regard to the required product quantity, delivery time, and part size of a specific product.

Based on the above four evaluation criteria, there are two ways of determining whether an AM system should be included in the design scope. First, an AM system will be considered only if all four of these criteria are met, an approach that implies a more rigorous evaluation. Second, an AM system will be considered when any one of the four criteria is fulfilled, indicating a more lenient approach to evaluation. Considering that this dissertation aims to realize a broader application of AM, the lenient approach to evaluation is suggested.

For the economic evaluation, cost and time estimations are recommended, as the build rate, purchasing price of the AM system, and cost factors are investigated in the datasheet. Figure 6-10 shows the manufacturing cost and build time when using *Concept Laser Mlab* to produce the holder, in which 25%, 50%, and 75% reductions in the volume are assumed. The cost factors for the estimation are machine cost, material cost, protective gas (nitrogen) cost, labor cost, and electricity cost [Yi19].

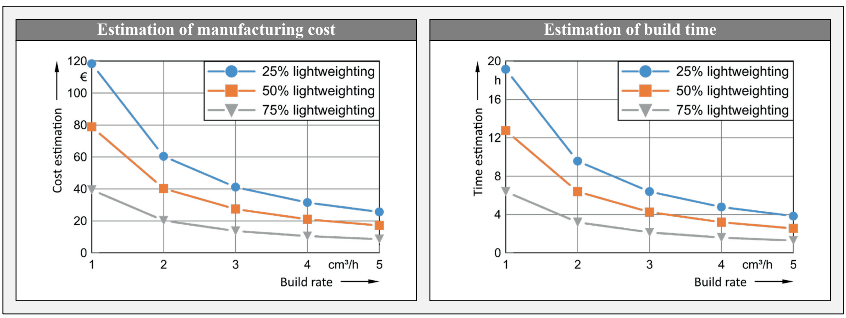



Figure 6-10: Cost and time estimations for the AM scenario for the holder

It can be seen that the cost and build time are significantly reduced as a result of an increase of the build rate. Considering that the production of the holder is a one-off task, conventional manufacturing offers no significant benefit over AM. Since the cost and time are still within the acceptable range of the design case, it is concluded that the *Concept Laser Mlab* SLM system is economically appropriate for this design case and will be considered in further design and evaluation activities.

### 6.2.4 Results of the situation analysis

The results of the situation analysis comprise the list of design requirements, the FAST diagram from the function analysis, descriptions of the process chain and production task of a conventional production scenario, the datasheets for the selected AM systems, and the results of the technical and economic evaluations. The first phase aims to specify the initial situation of a design case and to confirm that the implementation of AM has technical or economic benefits over conventional manufacturing. The results of this phase serve as the information input to the design and assessment activities introduced in the following subsections.

## 6.3 Phase 2: Topology optimization

After the specification of the initial situation, the product should be designed for AM. This dissertation adopts topology optimization, in which FEA is performed and the volume of a component is reduced to generate new geometries. The Siemens NX 12 CAD/CAE software with the integrated Topology Optimization add-on is used for the topology optimization [Mila19]. The workflow of the topology optimization process comprises three tasks: definition of design space, optimization setup, and generation of new geometries (see Figure 6-11).

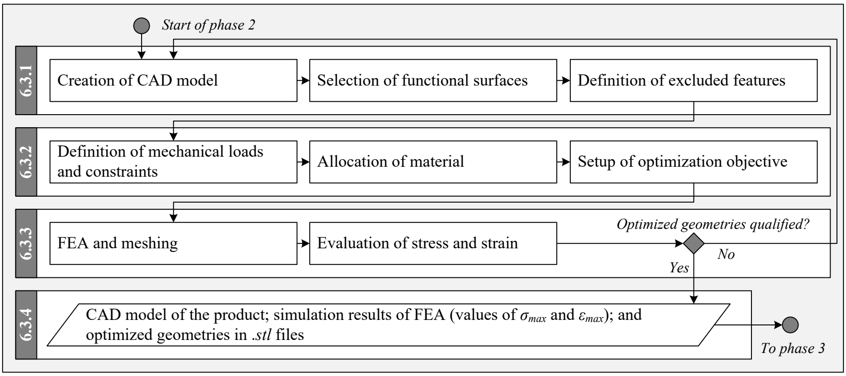



Figure 6-11: Overview of the steps involved in topology optimization

### 6.3.1 Definition of design space

Before the optimization process, the design space should be defined. The design space determines the maximum size of the geometrical features of a component that should remain within. The definition of design space consists of three steps: creation of a CAD model, selection of functional surfaces, and definition of excluded features.

**Creation of CAD model**

For modeling a component in AM, there are two main approaches. The first is to draw a CAD model of the product by stretching, rotating, and performing Boolean operations on lines, surfaces, and volumes using CAD software such as CATIA or NX. The second is to reconstruct the CAD model by 3D scanning the actual object. The main advantage of 3D scanning is that it is easy to perform and builds models quickly, while its disadvantage is that the data collected during the scanning process are influenced by the real environment, and the resulting models may thus have deviations from the real geometries of products. In comparison, a model developed in CAD software is error-free because the geometric features of the CAD model are not based on a data collection process but are instead defined by designers. Base on this comparison, the design example of the holder applies the drawing method, in which the Siemens NX 12 software is used to create a CAD model of the holder based on its technical drawing, as shown in Figure 6-12.

**Selection of functional surfaces**

In this step, the functional surfaces identified during the situation analysis are selected in the CAD model. In the next steps, forces and constraints, such as fixing and sliding, are added to the functional surfaces. For the design example, the through holes and screw holes are selected as functional surfaces, as shown in Figure 6-12.

**Definition of excluded features**

The final step involves defining the features to be excluded during the topology optimization. Exclusion indicates that a geometrical feature that will not be changed during the volume reduction process. In the CAD model for the design example, as shown in the final step of Figure 6-12, the features highlighted in red are excluded during the optimization process. The excluded features are defined as shell volumes of the holes with a thickness of 2 mm. The volume of the holder is approximately 25.5 cm³, and the volume of the excluded features is approximately 2.5 cm³. These values mean that the remaining space of 23 cm³ is the design space in which the new geometries are generated.

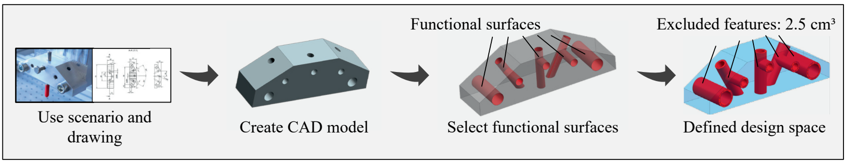



Figure 6-12: CAD model and design space

### 6.3.2 Optimization setup

After the design space is defined, the parameters should be set for the FEA and volume reduction. This process includes three steps: definition of mechanical loads and constraints, allocation of material, and setup of optimization objective.

**Definition of mechanical loads and constraints**

In FEA, the loads and constraints applied to a component constitute the mechanical boundary conditions to which the component is subjected. Examples of loads are torque, force, or pressure, and examples of constraints are fixing or sliding.

In general, the definition of loads and constraints is based on the actual use scenario. For example, in the design example of the holder, two 7-mm diameter through holes (holes 1 and 2) are used to secure the holder to the bracket, and a fixing constraint is therefore applied to them. During the scratch experiment, holes 6, 7, and 8 would be subjected to an axial force of up to 300 N. Based on the principle of taking the maximum value, a force of 300 N is applied to holes 6, 7, and 8. This value is chosen because, if the optimized component can withstand a force of 300 N, it will be able to withstand a force of less than 300 N.

**Allocation of material**

After the mechanical loads and constraints are applied, the material to be used for the component is defined. In the design example of the holder, 316L steel is defined according to the material data sheet provided by the machine's manufacturer. In practice, the properties of a material being processed in a build process may differ from those of the standard material. Nevertheless, since the topology optimization aims to generate new product geometries, the deviation between theoretical and actual material performance can be neglected in this step.

**Setup of optimization objective**

In terms of the Siemens NX 12 CAD software, the optimization objective can be defined as one of three types: minimize strain energy subject to mass target, minimize volume subject to safety factor, and minimize natural frequency subject to mass target. In the design example, the optimization objective is defined as the minimization of strain energy subject to mass target, in which the mass target should be defined by the designer.

To obtain a complete understanding of the geometry of the product at different defined mass targets, the design case of the holder takes different mass targets in seven different optimizations, as is explained in the next subsection.

### 6.3.3 Generation of new geometries

After the design space is defined and optimization parameters are configured, new product geometries can be generated through two steps: FEA and meshing and evaluation of stress and strain.

**FEA and meshing**

The FEA calculates the strain and stress of a component under a given mechanical boundary condition, in which the volumes with less strain and stress are removed, and the meshing creates a facet mesh that can be exported in the form of an *.stl* file, which is a standard CAD model format for AM.

Figure 6-13 shows the FEA and meshing of the design case of the holder, in which eight FEAs and seven meshing are carried out. First, under the defined mechanical loads and constraints, the FEA is executed for the original component (denoted as *0. FEA* in Figure 6-13). Thereafter, in the first optimization, as the optimization objective is defined as 90% of the original mass (10% mass reduction), the FEA and lightweighting are carried out to generate an optimum geometry aimed at minimization of the strain energy. The FEA image and the mesh of the first optimization in Figure 6-13 (denoted as *1. FEA and lightweighting* and *1. New facet mesh*, respectively) show the results of the optimum geometry. Thereafter, in the remaining second, third, fourth, fifth, sixth, and seventh optimizations, the mass reduction is defined from 20% to 70%, respectively.

From the results presented in Figure 6-13, it can be seen that in the first optimization, only materials around the two M7 through holes are reduced, since, for the first optimization, a mass reduction of only 10% is desired. During the second optimization, the mass reduction is increased to 20%; thus, the material in the middle of the holder begins to be removed. From the third to fifth optimizations, the material at the bottom of the holder gradually decreases with the increase in the desired mass reduction. By the seventh optimization, the mass reduction is defined as 70%, which means that only 30% of the original mass should remain, resulting in the material at the top and bottom of the holder being removed. When comparing the results of the seventh optimization with the original design space, it can be seen that the seventh facet mesh only contains the excluded features and the spreading-like struts that connect the excluded features, implying that 70% may be the maximum value of the possible mass reduction for the design case. Moreover, it should be noted that during the optimization process, the achieved mass may vary from the defined mass target. Figure 6-14 shows the target and achieved values.

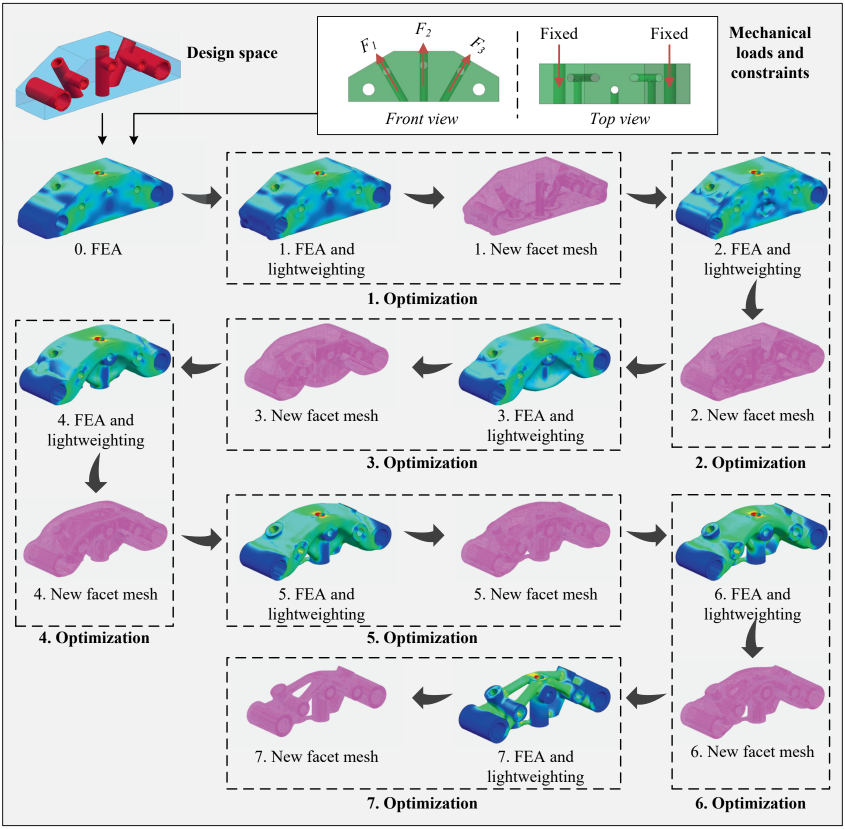



Figure 6-13: FEA and meshing of the holder

**Evaluation of stress and strain**

To evaluate the results of the optimization process, the maximum stress (von Mises stress, denoted as $\sigma_{max}$) and distortion (denoted as $\varepsilon_{max}$) are analyzed. Figure 6-14 summarizes the values of $\sigma_{max}$ and $\varepsilon_{max}$ for the design case of the holder and depicts their curves against the lightweighting factor, which is denoted as $\alpha$ and defines the ratio between the reduced mass ($\Delta m$) to the original mass ($m_0$) of a component, expressed by the following equation:

$$\alpha = \frac{\Delta m}{m_0} \qquad \text{Equation 6-1}$$

In Figure 6-14, it can be seen that the achieved mass value is always slightly lower than the defined mass target, which means that greater quantities of materials are removed during the optimization. In assessing the curves of $\sigma_{max}$ and $\varepsilon_{max}$, two stages can be observed: In the first stage, the values of $\sigma_{max}$ and $\varepsilon_{max}$ increase slowly in a linear fashion until the value of $\alpha$ is approximately 0.5. Thereafter, in the second stage, the growth of $\sigma_{max}$ and $\varepsilon_{max}$ shows exponential behavior. In general, higher values of $\sigma_{max}$ and $\varepsilon_{max}$ describe a stronger response of the material to mechanical loads and imply a higher risk of material failure; therefore, a 50% reduction in mass may be a critical point for the lightweighting of the holder, after which the risk of material failure will increase. Nevertheless, considering that the yield strength of 316L steel is approximately 385 MPa, the stresses in all FEAs are still within the permitted range, which means that all the optimized geometries qualify for final use.

| No. | Mass target (achieved value) in kg | $\sigma_{max}$ in MPa | $\varepsilon_{max}$ in µm |
|---|---|---|---|
| 0 | *No mass reduction* | 7.01 | 0.54 |
| 1 | 0.2 (0.16) | 7.46 | 0.56 |
| 2 | 0.18 (0.14) | 7.48 | 0.59 |
| 3 | 0.16 (0.13) | 7.88 | 0.64 |
| 4 | 0.13 (0.11) | 9.125 | 0.81 |
| 5 | 0.11 (0.09) | 9.486 | 0.91 |
| 6 | 0.09 (0.08) | 11.91 | 1.26 |
| 7 | 0.07 (0.05) | 20.13 | 2.95 |

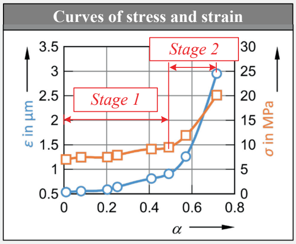



Figure 6-14: Stress and distortion values of the FEAs

### 6.3.4 Results of the topology optimization

The results of the topology optimization comprise the CAD model of the original product; the simulation results of the FEAs, including the values of $\sigma_{max}$ and $\varepsilon_{max}$; and the *.stl* files of the new geometries resulting from the FEA and lightweighting. These results both represent the output of the topology optimization process and serve as the input for next phases, as is explained in the next subsections.

## 6.4 Phase 3: AM workstation design

As described previously, at the workstation/machine level, an AM system consists of at least one AM machine and its associated devices. The third phase of the proposed method aims to completely define a specific AM system based on the selected AM machine from the situation analysis. To achieve this target, two subtasks are performed: definition of peripheral units and design of system layout (see Figure 6-15).

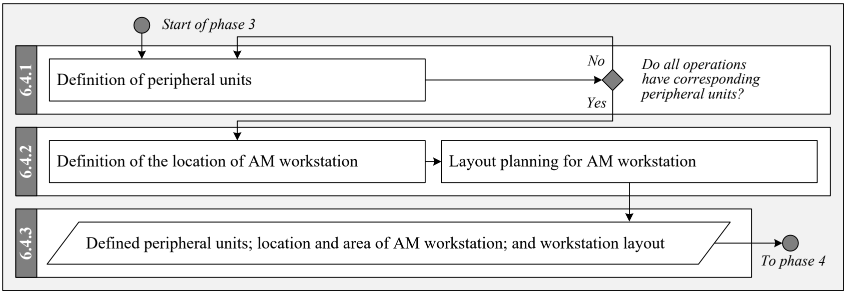



Figure 6-15: Overview of the steps for AM workstation design

### 6.4.1 Definition of peripheral units

As noted above, an AM workstation consists of an AM machine and peripheral units. Since the AM machine has already been selected and evaluated in the situation analysis, the corresponding peripheral units should be identified in this subtask. This is done in two steps: First, it is necessary to define the operations that will be carried out by the AM workstation. Second, it is necessary to assign one or more peripheral units to the execution of each operation. Figure 6-16 shows the workflow for defining the peripheral units for the AM workstation for the design example. According to the datasheet created in the situation analysis, the operations related to the *Concept Laser Mlab* include CAD model preparation, preparation of *.stl* files, powder screening and loading, powder recycling, removal of support structure, and post-processing. Since the data preparation and post-processing can be executed in a development department and a mechanical processing workshop, the remaining operations are identified as those that are carried out in the AM workstation. In the second step, the peripheral units are allocated to the operations. To execute powder screening and loading, a screen device is required to filter out powder with larger diameter. To enable the build process, the *Concept Laser Mlab* machine and a source of nitrogen gas are needed. To recycle the powder, a vacuum cleaner and a handling station are required. To remove the support structure from the substrate, a bench vise is needed. In addition, the screen device and the bench vise cannot be placed on the ground; therefore, two desks are allocated to them.

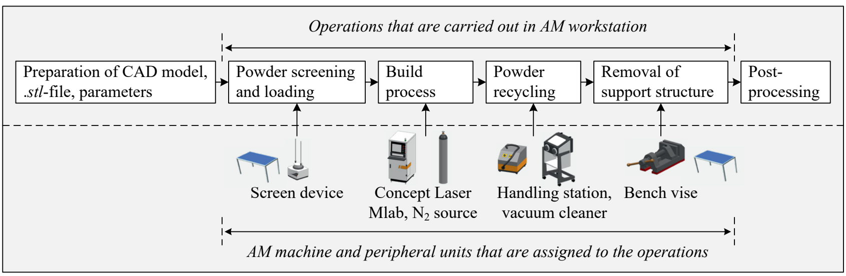



Figure 6-16: Definition of peripheral units for the AM workstation

Finally, it is necessary to determine whether each operation has corresponding peripheral units. Once all the peripheral units are assigned, the following step is to design their layout, which is described in the next subsection. Otherwise, the selection and allocation of the peripheral units should be repeated.

### 6.4.2 Design of system layout

At the workstation/machine-level, the layout of an AM workstation describes the arrangement of the included AM machine and peripheral units located in a manufacturing cell. Therefore, the process of laying out the design of the AM comprises the following two steps: definition of the location of AM workstation and the layout planning for AM workstation.

**Definition of the location of AM workstation**

Before determining the layout of an AM workstation, it is necessary to determine the location and size of the workstation that is needed. In the design example of the holder, according to the datasheet provided by the machine manufacturer, the *Concept Laser Mlab* SLM system occupies an area of 0.86 $m^2$. The areas required for the handling station, vacuum cleaner, screen device, $N_2$ gas tank, and bench vise are 0.48 $m^2$, 0.19 $m^2$, 0.16 $m^2$, 0.04 $m^2$, and 0.12 $m^2$, respectively. Therefore, by adding the values of the areas for the AM machine and peripheral units, the minimum area required for the workstation is determined to be 1.85 $m^2$. However, the bench vise and screen device are placed on desks with the same size of 2 $m^2$, as shown in Figure 6-17. Therefore, the minimum area required for the workstation is 5.57 $m^2$, which is the sum of the areas required for the AM machine (0.86 $m^2$), handling station (0.48 $m^2$), vacuum cleaner (0.19 $m^2$), $N_2$ gas tank (0.04 $m^2$), and two desks (4 $m^2$). The required minimum area does not, however, include the area required for human activities. Therefore, for the design case, a room with a total area of 17.16 $m^2$ is allocated to the workstation for the AM system, as depicted in Figure 6-17.

**Layout planning for AM workstation**

After the location and area of an AM workstation are defined, the AM machine and the peripheral units are arranged in a specific layout. In the design example of the holder, the Siemens Plant Simulation software is used for the layout design; Figure 6-17 shows the result.

Since the implementation of SLM requires a number of human operations before and after the build process, the principle for the system layout is that the SLM machine and peripheral units are allocated near the wall of the workstation to allow workers to move in the middle of the workstation. Figure 6-17 shows three operations: powder screening, powder recycling, and the removal of the support structure. In the powder screening operation, the powders are filtered through a vibrating screening net with a specific diameter. After the build process, the handling station is connected to the *Concept Laser Mlab* to remove the build platform. During powder recycling, a vacuum cleaner is used to recycle the powders. Following the powder recycling, the part is removed from the platform, and the support structure is then removed from the part using the bench vise.

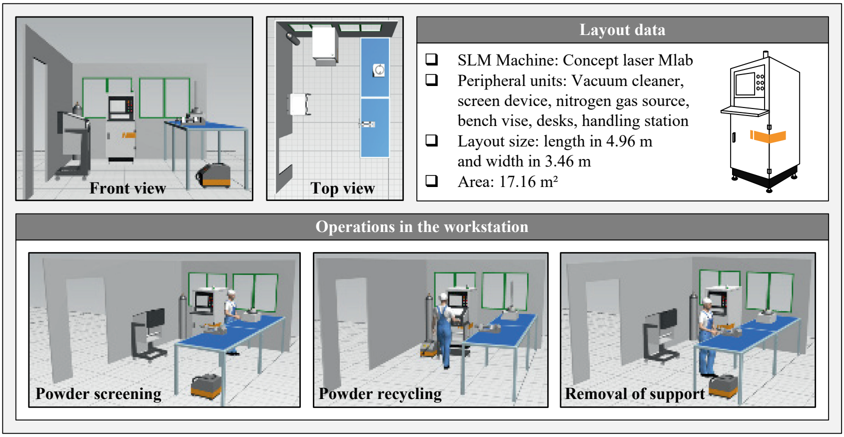



Figure 6-17: Defined AM machines and peripheral units

### 6.4.3 Results of the AM workstation design

The results of this phase include the defined AM workstation, which includes the AM machine, the peripheral units, and the location of, as well as the area required for, the AM workstation. Since the AM workstation can be designed in different solutions, in which different AM machines or peripheral units may be used, leading to different levels of energy performance, varying the workstation design can also be a means of proposing different AM design solutions. In line with the results of the topology optimization, the results of the workstation design serve as the input for the next phases, which are explained in the following subsections.

## 6.5 Phase 4: Build process design

Since the product and AM workstation have been designed, the fourth phase aims to define the build process, in which the process parameter set is first defined and the process performance is evaluated using a thermal-structural simulation. Thereafter, according to the desired functionality of the functional surface, any necessary post-processing required to improve the material properties, geometrical accuracy, or surface quality of the produced components is identified. Figure 6-18 shows the workflow of this phase, which includes two subtasks: definition of process parameter set and definition of post-processing steps.

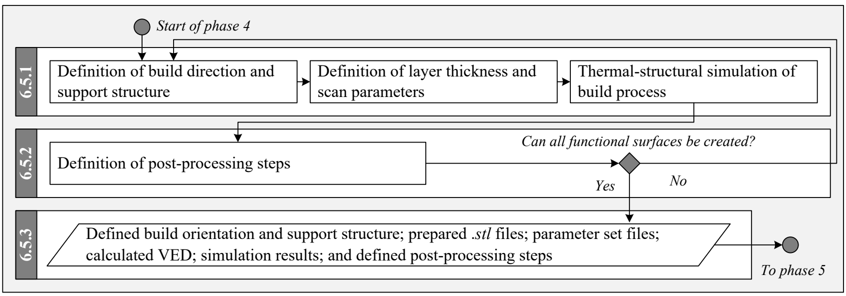



Figure 6-18: Overview of the steps for build process design

### 6.5.1 Definition of process parameter set

The first subtask of this phase is the definition of the process parameter set, in which the following three steps are performed: definition of build direction and support structure, definition of layer thickness and scan parameters, and thermal-structural simulation of build process.

**Definition of build direction and support structure**

Before defining other process parameters, the build direction of a part is first defined, as the direction has a significant impact on the final material property, process performance, and build time. In general, the definition of build direction in SLM follows the 45° rule, which states that if the angle between a surface and a platform is less than 45°, this surface is called a down surface; it is necessary to add a support structure to such a surface to prevent it from overhanging and collapsing. In addition, the support structure also enables heat dissipation during the fusion of layers to reduce residual stresses in a final product.

Figure 6-19 shows the seven different ways of placing the holder, in which the angle between the bottom surface of the holder and the platform increases from 0° to 90° (i.e., from a "standing" to a "lying down" build-up position). Due to the different positioning angles, different support structures are required. For example, before the angle is increased to 45°, supports are added to the circular surfaces of the two cylinders on both sides. After the angle is increased to above 45°, the supports are no longer attached to the circular surfaces but instead to the toroidal surfaces. In general, the volume of the support structure is not as large or as small as it should be. An optimal support structure would be one that allows minimal deformation due to the melting and cooling of layers during the build process. The deformation of a workpiece can only be determined by means of a thermal-structural simulation, as is described in the following paragraphs.

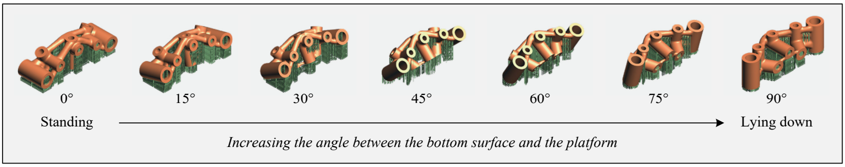



Figure 6-19: Definition of build orientation and support structure

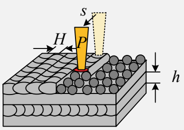
**Definition of layer thickness and scan parameters**

In general, the parameter settings of a build process (e.g., layer thickness, laser speed, hatching space, and laser power) have a significant impact on the material properties of the final product; therefore, manufacturers of AM machines usually provide recommended settings for different materials to ensure product quality. In cases in which users do not have access to the recommended parameter settings, it is suggested that volumetric energy density (VED) be used to evaluate process parameter combinations. Existing research notes that the material density of a part produced by SLM has a significant correlation with VED, which is related to the laser power ($P$), laser speed ($v$), layer thickness ($h$), and hatching distance ($H$). This correlation is expressed as follows [Meie08]:

$$VED = \frac{P}{vhH}$$ Equation 6-2

Specific VED value ranges indicate optimum performance for different materials. For example, for 316L stainless steel, a VED value between 40 and 90 J/mm³ enables the highest density and lowest surface roughness of a component produced by SLM [Meie08]. However, the material properties related to SLM are a very comprehensive research topic. In addition to VED, the product quality of an SLM process is also related to the properties of the powder used for a build, such as particle size, composition, and whether the powder is virgin or recycled. Figure 6-20 shows the recommended process parameter settings identified in the literature for the use of 316L materials in SLM [Yasa10, Grec20, Krut12, Wei11, Krut10, Yadr10, Spie09, Yasa09].

| P (W) | s (mm/s) | h (µm) | H (µm) | Highest $\rho_{Rel}$ (%) | Source |
|---|---|---|---|---|---|
| 30 to 90 | Adjusted | 25 to 45 | 42 to 84 | up to 99.9 | [Grec20] |
| 98 | 90 to 150 | 70 | 100 to 150 | up to 98 | [Wei11] |
| 85 to 105 | 300 | 20 to 60 | 112 to 125 | 98.8 to 99.2 | [Yasa09] |
| 104 | 300 to 800 | 30 | 130 | 99.3 to 99.5 | [Spie09] |
| 100 | 300 | 30 | 81 to 126 | 98.4 to 98.9 | [Yasa10] |
| 50 | 120 | 40 | 120 | more than 99 | [Yadr10] |
| 105 | 380 | 20 to 40 | 125 | 99.25 to 99.8 | [Krut10] |
| 100 | 175 to 380 | 60 | 126 | 98.5 to 98.8 | [Krut12] |




**Legend:**
*H*: Hatching distance
*s*: Scan speed
*P*: Laser power
*h*: Layer thickness
$\rho_{Rel}$: Relative density

Figure 6-20: Recommended process parameters for SLM with 316L powders

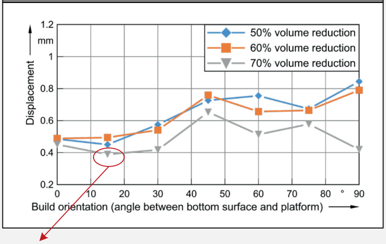
For the design example of the holder, two process strategies are defined. The first is a fast-scanning strategy, in which *P*, *v*, *h*, and *H* are respectively defined as 90 W, 300 mm/s, 0.03 mm, and 0.15 mm. The second strategy is a slow strategy, in which *P*, *v*, *h*, and *H* are respectively defined as 50 W, 250 mm/s, 0.02 mm, and 0.15 mm. The material used for the build is defined as 316L stainless steel powder with the same VED value of 66.67 J/mm³ for both parameter settings. Therefore, according to the hypothesis that the same VED leads to the same material property, the material performance for both parameter settings should be equivalent.

**Thermal-structural simulation of build process**

After the process parameters are defined, a thermal-structural simulation is required to evaluate the deformation of material used due to the melting and cooling of layers. Figure 6-21 shows the simulation results, namely the maximum displacement due to thermal stress, for holders that have been lightweighted by 50%, 60%, and 70%, in which the build orientation angle is increased from 0° to 90°.

| Build orientation | Max. Displacement of part (mm) | | |
|---|---|---|---|
| | 50% volume reduction | 60% volume reduction | 70% volume reduction |
| 0° | 4.85E-01 | 4.88E-01 | 4.51E-01 |
| 15° | 4.50E-01 | 4.94E-01 | 3.89E-01 |
| 30° | 5.75E-01 | 5.41E-01 | 4.17E-01 |
| 45° | 7.26E-01 | 7.59E-01 | 6.53E-01 |
| 60° | 7.55E-01 | 6.56E-01 | 5.13E-01 |
| 75° | 6.73E-01 | 6.64E-01 | 5.78E-01 |
| 90° | 8.44E-01 | 7.90E-01 | 4.19E-01 |

**Plot of displacement with build orientation**




*Thermal-structural simulation of the part with 70% volume reduction*

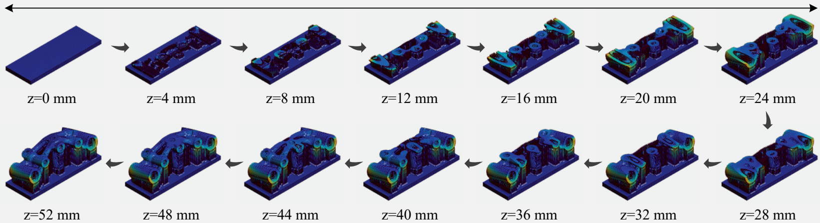



Figure 6-21: Thermal-structural simulation of the build process for the design case

From the table and the plot in Figure 6-21, it can be seen that, for all three optimized geometries, the minimum displacement is always observed at an angle of 15°, which implies that the build orientation with an angle of 15° between the bottom surface of the holder and platform is optimal.

### 6.5.2 Definition of post-processing steps

To achieve the desired product functionalities, two post-processing steps may be needed for SLM. The first post-processing is heat treatment to relieve the residual stress, while the second post-processing step is subtractive manufacturing to improve the geometrical accuracy or surface quality of the final product. In general, design requirements determine whether post-processing is needed. For example, in the design example, the holder encompasses three thread holes whose geometrical accuracy and surface finish cannot be achieved by SLM. Therefore, the required drilling process is defined as a post-processing step.

### 6.5.3 Results of the build process design

In general, the definition of the process parameters is executed with AM pre-processing software. For example, when defining the build orientation and support structure, it is not necessary to attach the support structure manually. By importing *.stl* files into pre-processing software, the support structure can be generated automatically. In this dissertation, *Netfabb* is used to prepare *.stl* files and generate supports, and *Amphyon* is used to perform the thermal-structural simulation of the build processes [Addi20, Auto19]. The results of this phase include a defined build orientation and generated supports, processed *.stl* files and parameter set files, simulation results, calculated VED values, and defined post-processing steps. Based on these results, the energy performance of each design solution can be evaluated, as is discussed in the next subsection.

## 6.6 Phase 5: EnPI-based assessment

The evaluation of the energy performance of all design solutions for AM is based on the quantification of EnPIs that represent measures of energy performance. The EnPI-based assessment phase encompasses three subtasks: energy simulation, quantification of EnPIs, and assessment of EnPIs. Figure 6-22 shows the workflow of the subtasks for this phase.

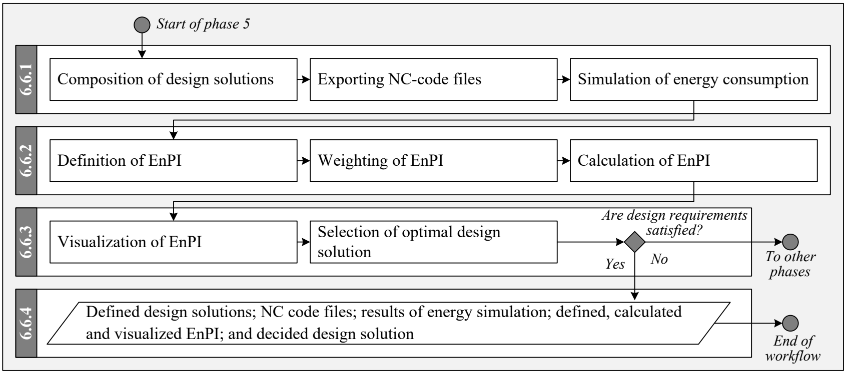



Figure 6-22: Overview of the steps for the quantification of EnPIs

### 6.6.1 Energy simulation

The first subtask in an energy performance quantification and assessment is to simulate the energy consumption of each design solution, in which the following three steps are carried out: composition of design solutions, exporting NC code files, and simulation of energy consumption using the simulation tool, the development of which is described in Chapter 4.

**Composition of design solutions**

The first step in quantifying EnPIs is to present various product, process, and workstation designs in the form of different design solutions. For the design case, by considering the results of the topology optimization, AM workstation design, and build process designs, eight design solutions are determined and regarded as candidates for the energy performance assessment (see Figure 6-23). In the topology optimization, the new geometries with approximately a 50% and 70% reduction in volume—representing the lightweighting with less strain increase and less material, respectively—are chosen as the new geometries that should be considered in the composition of design solutions. With regard to the AM workstation design, the *Concept Laser Mlab* and the *Ultimaker 3* are identified as two AM workstations capable of handling the production task of the new product design by using 316L and polylactic acid (PLA). The results of the build process design are two parameter sets, in which slow and fast scanning strategies are defined. Finally, considering three factors with two levels each leads to eight design solutions ($2^3$=8).

After the design solutions are determined, it must be determined whether the design requirements identified in the situation analysis are considered. For the design case, two relevant design requirements are that a volume reduction of at least 50% is expected and that the selected AM process should be capable of producing a holder with the desired quality. For the first requirement, the two product designs with 50% and 70% weight reductions are considered, and the first requirement is therefore satisfied. For the second design requirement, both SLM and FDM systems are able to produce a holder with the desired mechanical performance; thus, this requirement is also fulfilled.

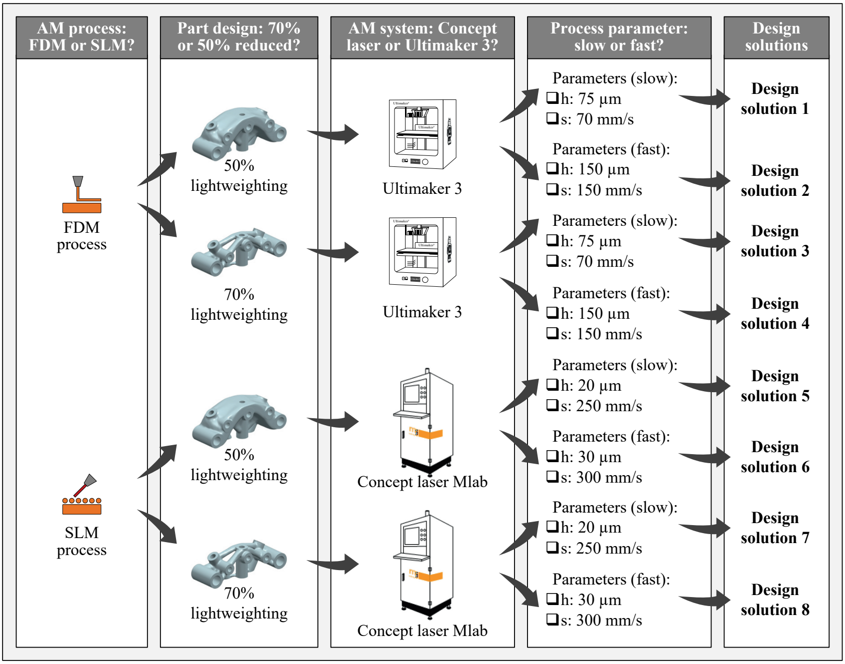



Figure 6-23: Determination of design solutions for the design case

**Exporting NC code files**

As described in Section 4, this dissertation adopts an *NC code and database-driven simulation* approach; therefore, the first step of the energy simulation is to set the process parameters of the build process and output them in the form of NC code files. In this step, the NC code file for SLM is the *.lsr* file format provided by *Netfabb*, while the NC code for FDM is the *.gcode* file generated by *Ultimaker Cura*.

**Simulation of energy consumption**

Once the NC codes are exported, they are then imported into the simulation tool. Thereafter, the energy simulation is performed for each design solution, and the results thereof are stored in *.txt* files. The energy consumptions of all design solutions in the design example are summarized in the $E_{total}$ rows in Figure 6-25.

### 6.6.2 Quantification of EnPIs

The EnPIs represent energy performance and provide a comparison baseline for all design solutions. To quantify the EnPIs for each design solution, the following three steps are carried out: definition of EnPIs, weighting of EnPIs, and calculation of EnPIs.

**Definition of EnPIs**

As described in Section 5, different design cases require individual EnPIs. For the design case of the holder, with respect to the defined design requirements, the following four EnPIs are defined: total energy consumption ($E_{total}$), specific energy consumption (SEC), the safety factor-energy consumption ratio (SFER), and energy cost (EC). These EnPIs are described below.

The total energy consumption ($E_{total}$) refers to the sum of the energy consumption of an AM machine ($E_{AM}$) and the peripheral units ($E_{pu}$) in a build process, and it is defined as the following equation:

$$E_{total} = E_{AM} + \sum E_{pu} \qquad \text{Equation 6-3}$$

For the *Concept Laser Mlab*, the peripheral units with energy consumption are the vacuum cleaner and screen device, while, for the *Ultimaker 3*, the vacuum cleaner is the only peripheral unit with energy consumption. The SEC defines the ratio between the total energy consumption ($E_{total}$) and the volume of the part ($V_{part}$), and it is defined by the following equation:

$$SEC = \frac{E_{total}}{V_{part}} \qquad \text{Equation 6-4}$$

A safety factor (SF) defines the ratio between the yield strength and the maximum stress of a part under certain mechanical conditions. The safety factor-energy consumption ratio (SFER) defines the ratio between a safety factor and total energy consumption ($E_{total}$) for a specific part, and it is expressed by the following equation:

$$SFER = \frac{SF}{E_{total}} \qquad \text{Equation 6-5}$$

The final EnPI is the energy cost (EC), which is the product of the total energy consumption ($E_{total}$) and the electricity price, and it is expressed in Equation 6-6. In Germany, the electricity price for industrial use is 0.19 €/kWh [Euro20].

$$EC = E_{total} \times electrcity\ price \qquad \text{Equation 6-6}$$

**Weighting of EnPIs**

After the EnPIs are defined, they are weighted using the *pairwise comparison* approach, as described in Section 5. For the design case, the general design requirement is to use less energy and to reduce the costs in producing the holder. Therefore, $E_{total}$ and EC are evaluated with the highest priority level. SEC indicates the energy consumption per material unit and is widely used for build tasks with multiple parts. However, the design example of the holder is a one-off task, and its SEC is therefore defined as having a middle priority level. For the SFER, it is known that the yield strengths of PLA and 316L are 49.5 MPa and 385 MPa, respectively, and that the maximum stress of all design solutions is only 20.13 MPa (for lightweighting by 70%) [Conc19b, Ulti18]. Therefore, since the safety factor is higher than 1 for both the 316L and PLA materials, which implies that the optimized parts always qualify for final use, the SFER is assigned a low priority level. Figure 6-24 depicts the *pairwise comparison* and weighting of the EnPIs.

| EnPI | Priority level | EnPI | | | | Score | WF |
|---|---|---|---|---|---|---|---|
| | | $E_{total}$ | SEC | SFER | EC | | |
| $E_{total}$ | High | | 6 | 6 | 3 | 15 | 0.37 |
| SEC | Middle | 1 | | 6 | 1 | 8 | 0.19 |
| SFER | Low | 1 | 1 | | 1 | 3 | 0.07 |
| EC | High | 3 | 6 | 6 | | 15 | 0.37 |
| | | | | | Sum: | 41 | 1 |

Figure 6-24: Weighting of EnPIs for the design case

### Calculation of EnPIs

The calculation of EnPIs for a design case can be handled on three levels: original, normalized, and aggregated EnPIs. Figure 6-25 shows the calculation of EnPIs for the design case of the holder. It can be seen that the calculation of original EnPIs requires the values of other product- and material-related factors, such as part volumes, yield strength, and safety factors for PLA and 316L steel powder (denoted as SF_PLA and SF_316L in Figure 6-25).

Following the calculation of the original EnPIs, the ranges of the EnPI values for all design solutions are determined, according to which the normalized EnPIs′ are calculated. It should be noted that the normalization of an EnPI can be based on either Equation 5-1 or Equation 5-2, depending on whether the general evaluation rule follows the principle of "the higher, the better" or "the lower, the better." For $E_{total}$, SEC, and EC, the general rule is that a lower value implies better performance, while, for SFER, a higher value indicates better performance because the energy consumption is a denominator, not a numerator. Therefore, the normalization of $E_{total}$, SEC, and EC for the *i*-th solution can be expressed as follows:

$$E_{total(i)}{}' = \frac{\max(E_{total}) - E_{total(i)}}{Range(E_{total})}$$

$$SEC_{(i)}{}' = \frac{\max(SEC) - SEC_{(i)}}{Range\left(SEC_{(i)}\right)} \qquad \text{Equation 6-7}$$

$$EC_{(i)}{}' = \frac{\max(EC) - EC_{(i)}}{Range(EC)}$$

The normalization of SFER is given by the following equation:

$$SFER_{(i)}{}' = \frac{SFER_{(i)} - \min(SFER)}{Range(SFER)} \qquad \text{Equation 6-8}$$

Following the normalization, the WF values shown in Figure 6-24 are aggregated with normalized EnPIs′; therefore, Equation 5-4 can be modified into the following equations:

$$E''_{total(i)} = E'_{total(i)} \times 0.37$$

$$SEC''_{(i)} = SEC'_{(i)} \times 0.19$$

$$SFER''_{(i)} = SFER'_{(i)} \times 0.07 \qquad \text{Equation 6-9}$$

$$EC''_{(i)} = EC'_{(i)} \times 0.37$$

Finally, based on Equation 5-5, the final energy performance score of the *i*-th solution, denoted as EnPI″(Sum) in Figure 6-25, can be rewritten into the following equation:

$$EnPI''_{(i)}(\text{Sum}) = E''_{total(i)} + SEC''_{(i)} + SFER''_{(i)} + EC''_{(i)} \qquad \text{Equation 6-10}$$

Figure 6-25 presents the results of the calculation of the original EnPIs, normalization, and aggregation of the EnPIs.

**Level III: Aggregated EnPI (EnPI″)**

| | Design solutions | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| $E_{total}''$ | 0.33 | 0.36 | 0.35 | 0.37 | 0 | 0.15 | 0.12 | 0.22 |
| SEC″ | 0.18 | 0.2 | 0.17 | 0.19 | 0.07 | 0.12 | 0 | 0.08 |
| SFER″ | 0.02 | 0.05 | 0 | 0.01 | 0.04 | 0.07 | 0.01 | 0.03 |
| EC″ | 0.33 | 036 | 0.35 | 0.37 | 0 | 0.15 | 0.12 | 0.22 |
| **EnPI″(Sum)** | 0.86 | ***0.95*** | 0.86 | 0.93 | ***0.1*** | 0.49 | 0.26 | 0.56 |

**Level II: Normalized EnPI (EnPI′)**

| | Design solutions | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| $E_{total}'$ | 0.89 | 0.97 | 0.95 | ***1*** | ***0*** | 0.41 | 0.34 | 0.61 |
| SEC′ | 0.95 | ***1*** | 0.87 | 0.95 | 0.33 | 0.62 | ***0*** | 0.4 |
| SFER′ | 0.28 | 0.65 | ***0*** | 0.17 | 0.51 | ***1*** | 0.15 | 0.4 |
| EC′ | 0.89 | 0.97 | 0.95 | ***1*** | ***0*** | 0.41 | 0.34 | 0.61 |

**Level I: Original EnPI**

| | Design solutions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| EnPI | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Range |
| $E_{total}$ (kJ) | 4.04e+3 | 2.45e+3 | 2.97e+3 | ***1.87e+3*** | ***2.23e+4*** | 1.39e+4 | 1.54e+4 | 9.75e+3 | 2.05e+4 |
| SEC (kJ/cm³) | 2.95e+2 | ***1.79e+2*** | 4.56e+2 | 2.86e+2 | 1.63e+3 | 1.02e+3 | ***2.36e+3*** | 1.50e+3 | 2.18e+3 |
| SFER (1/kJ) | 1.61e-3 | 2.66e-3 | ***8.28e-4*** | 1.32e-3 | 2.27e-3 | ***3.64e-3*** | 1.24e-3 | 1.96e-3 | 2.82e-3 |
| EC (€) | 2.13e-1 | 1.29e-1 | 1.57e-1 | ***9.84e-2*** | ***1.18e+0*** | 7.34e-1 | 8.11e-1 | 5.15e-1 | 1.08e+0 |

| | $V_{part}$ (cm³) |
|---|---|
| **50% reduction** | 13.69 |
| **70% reduction** | 6.52 |

| | SF_PLA | SF_316L |
|---|---|---|
| **50% reduction** | 6.51 | 50.66 |
| **70% reduction** | 2.46 | 19.13 |

Figure 6-25: Calculation and aggregation of EnPIs for the design case

### 6.6.3 Assessment of EnPIs

Based on the quantification of the EnPIs, the energy performance of each design solution is assessed in two steps: visualization of EnPIs and selection of optimal design solution.

#### Visualization of EnPIs

To evaluate the energy performance of design solutions, the values of all normalized and aggregated EnPIs are visualized. In the design example of the holder, stacked area charts and stacked percentage bar charts are used to visualize the normalized and aggregated EnPIs, as depicted in Figure 6-26. From the two stacked area charts, two findings can be observed: First, in general, the FDM-related design solutions (solutions 1 to 4) have overall higher performance values than the SLM-related solutions (solutions 5 to 8). The main reason for this difference is that FDM-based solutions have less overall total energy consumption than those solutions based on SLM. Second, after the normalization, solution 2 scores significantly higher than the other solutions; after the aggregation, solution 2 still has the highest score of 0.95, but it is closely followed by solution 4, with a difference of 0.02 between the two solutions. From the two stacked percentage bar charts, it can be observed that the composition of the SFER in each bar is reduced after the aggregation. In addition, with the exception of solution 5, the composition of the SEC in each bar is also reduced after the aggregation. These reductions are due to the fact that the SEC and SFER have low and middle priority levels, respectively, and the priority levels, as well as the resulting weighting factors, have a certain impact on the results of the aggregation of the EnPIs.

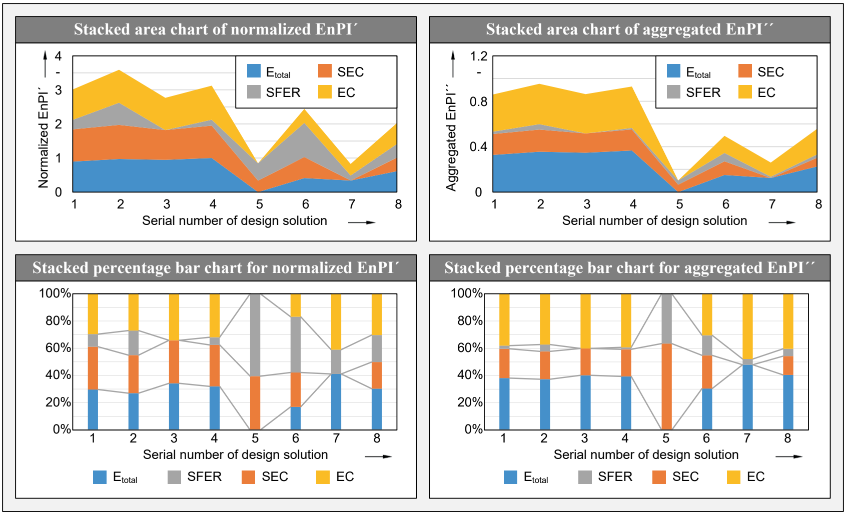



Figure 6-26: Stacked area chart of normalized and aggregated EnPIs for the design case

### Selection of optimal design solution

Finally, based on the visualized EnPIs, an optimal design solution is selected. In addition, when selecting the optimal solution, it is necessary to determine whether all design requirements defined during the situation analysis have been satisfied. Should one or more requirements not have been met, the previous phases, such as the topology optimization, AM workstation design, and build process design, should be repeated until all design requirements are fulfilled.

For the design example of the holder, it can be seen that solution 2 has the highest final performance score and should thus be selected as the optimal solution. In the evaluation, the total energy consumptions of the SLM-related solutions were found to be higher overall than those of the FDM-related solutions, as the melting of metals requires more energy than the melting of plastics. However, metal parts can offer longer lifespans than plastic parts. Therefore, when considering this benefit, solution 8 should be implemented, as it scores the highest performance value among the SLM-related solutions. In conclusion, for the design example of the holder, solutions 2 and 8 exhibit the best energy performance and should be considered for further implementation, which is discussed in Section 6.7.1.

### 6.6.4 Results of the EnPI-based assessment

The initial results of the EnPI-based assessment are the defined design solution, NC codes, the results of the energy simulation, and the defined and calculated EnPI values. The final result of this phase is the optimal design solution, which is determined based on the evaluation of the EnPIs. Moreover, the selection of the optimal solution also represents the end of the eco-design for AM method proposed in this dissertation.

## 6.7 Discussion of the method

### 6.7.1 Follow-up of the implementation of the optimized holder

Eco-design for AM only focuses on design issues and excludes the application phase; thus, the implementation of the optimized holder was not described in previous subsections, as the focus was on introducing the design and evaluation activities. However, the feasibility of the proposed method can only be demonstrated by the implementation of the design solution, in which the optimized holders are produced based on solutions 2 and 8 (see Figure 6-27). In the application, the optimized holders are mounted on the equipment used for the scratch experiment. During the scratch experiment, it was observed that the optimized holders are functionally feasible for final use.

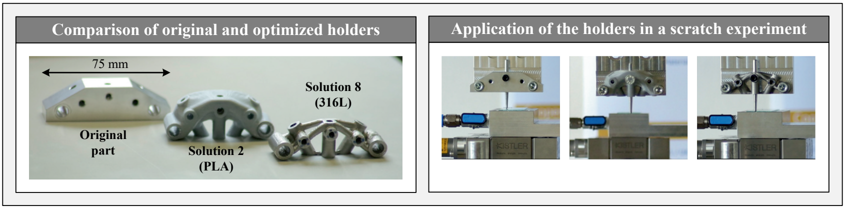



Figure 6-27: Implementation of the optimized holders

### 6.7.2 General design mechanisms and the modified workflow

The proposed method belongs to the design phase of the lifecycle of an AM product, which mainly consists of design issues for products, AM systems, and build processes. In practice, different designers have individual design problems; therefore, this dissertation presents the following four generalized design mechanisms, in which the workflow of the proposed method can be modified to other forms, as depicted in Figure 6-28.

- **Product-specific design mechanism:** This design mechanism refers to designers only varying product-related parameters (e.g., geometry or material) to propose design solutions with different levels of energy performance. Using this mechanism, novel approaches for product design, such as topology optimization, the use of lattice structures, and part consolidation, are applied. In the workflows for product-related design cases, the second phase is the design focus and the parameters related to the topology optimization are varied, while the parameters for AM workstation design and build process design remain the same.
- **System-specific design mechanism:** A system-specific approach to design refers to designers only varying the parameters of AM workstations to propose different design solutions. An example of such a design case would be a situation in which designers already have a given product and build process design and must select one of three different AM

machines to perform the build task. Therefore, in the workflows of the system-related approach to design, the design focus is the AM workstation design phase, while the parameters for the product design and build process design remain the same for all solutions.

- **Process-specific design mechanism:** This design mechanism refers to designers viewing the build process design as the design focus and proposing different design solutions by varying parameters such as build speeds, layer thicknesses, and build orientation. Meanwhile, the parameters related to the product and AM workstation are consistent for all solutions.
- **Multiple design mechanism:** A design case with a multiple design mechanism involves designers varying parameters from at least two of the phases involved in designing product, AM workstation, and build process to propose design solutions. The design example of the holder belongs to this type.

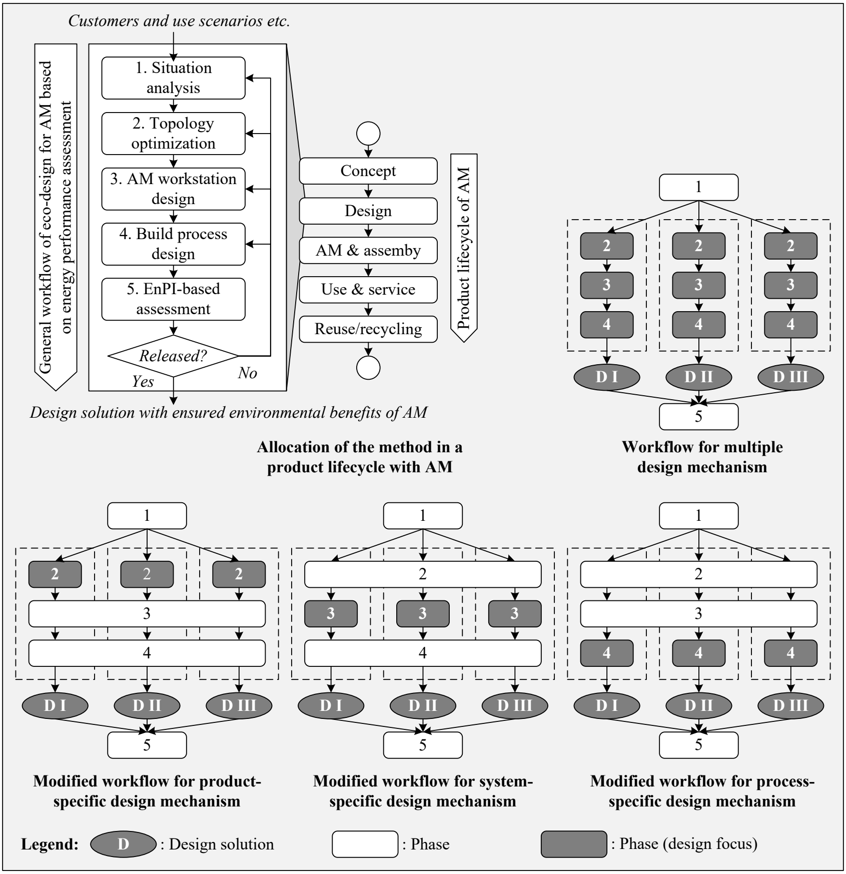



Figure 6-28: Four general design mechanisms and their modified workflows

The selection of a workflow for a specific case depends on the designers' selection of a design mechanism. For example, if a specific product design is given, then designers only need to focus on designing the AM system and build process, or if an AM system has been already purchased, then designers only need to focus on the product and build process design.

### 6.7.3 Evaluation of the method

Based on the analysis of the design case and the comparison with other eco-design for AM methods, the method proposed in the dissertation, including the simulation tool and assessment model, has been proven to be feasible for enabling eco-design for AM. With respect to the requirements defined in Chapter 2.3.3, the proposed method has the following benefits:

- ❑ **Requirement 1: Description of the environmental performance of AM:** The method proposed in this dissertation focuses on environmental performance. Since other, non-energy-related impact categories are not taken into account, the benefit is the reduced complexity in terms of describing the environmental performance of AM. In the assessment model, the EnPIs are normalized, weighted, and aggregated to a score representing the final energy performance of AM. Therefore, a benefit of the proposed method is the improved comparability of multiple design solutions within the same evaluation baseline.
- ❑ **Requirement 2: Enabling convenient and reliable energy prediction of AM processes:** In comparison with experiments, which can be are cost- and time-intensive, the main benefit of the simulation tool is the reliable and efficient quantification of the energy demands of AM processes in the middle design phase.
- ❑ **Requirement 3: Integration of assessment and design activities:** While the NC code represents the final result of the design of a build process, it is also required as the input for the energy simulation. In this sense, the NC code serves as the interface that connects design and assessment activities. Moreover, the simulation model is implemented in MATLAB, which implies the possibility of the model being transferred to other programming platforms and integrated to CAD or AM pre-processing software.
- ❑ **Requirement 4: Integrated consideration of design benefits and environmental impacts:** The assessment model allows the combination of energy and non-energy parameters to create EnPIs. This leads to the benefit that variables used to indicate design performance can also been integrated in EnPIs and considered during the evaluation process. In addition, the aggregation of EnPIs with weighting factors implies that subjective perceptions are reflected in the EnPIs and integrated with objective perceptions (quantified energy and non-energy variables of AM) during the evaluation. This leads to the benefit that the chosen design solution will more closely fit the expectations of designers.
- ❑ **Requirement 5: Convenience, ease-of-use, and robustness:** The simulation tool, assessment model, and the workflows summarized in the five phases of the method provide a detailed description of the activities involved in conducting eco-design for AM. This leads to the benefit of the improved usability of the proposed framework. Moreover, although the latest version of the simulation tool only contains power data for two AM systems, it can easily be extended. Even if designers predict energy demand with other empirical models instead of applying the simulation model proposed in this dissertation, the steps involving the topology optimization, AM workstation design, build process design, and calculation and assessment of EnPIs can still be performed. This leads to the benefits of the improved flexibility and modifiability of the method.

# 7 Use cases

To demonstrate the feasibility of the proposed simulation tool, assessment model, and eco-design for AM method, three use cases are performed. In the first use case, the proposed method is used to design the cam plate of a conveyor system. The second use case concerns the implementation of the proposed method in the design of the process of producing a ring with a lattice structure. Finally, the last use case presents the application of the proposed method to combine the energy performance assessment with the cost estimation of an optimized bottle opener in different process designs. Through these use cases, the usability, robustness, simulation capability, and reliability of the proposed eco-design for AM framework are well demonstrated.

## 7.1 Use case 1: Optimization of a cam plate

### 7.1.1 Situation analysis of the cam plate

The component considered in the first use case is a cam plate driven by a chain gear. The entire equipment is used to produce cylindrical rods, and the cam plate is a component of the conveying system (see Figure 7-1). In the production process, cylindrical rods are produced and then fall onto the cam plate, which rotates clockwise to push the rods onto the conveyor band with a certain takt time. The exterior diameter of the cam plate is approximately 100 mm, and its mass is approximately 433 g. The entire system is still in development and has not yet been manufactured, and the cam plate is to be produced using milling with 16MnCr5 steel. In this design case, the design objective is defined as the lightweighting of the cam plate to save material and reduce energy use by means of AM. Therefore, this design case implies a product-related design mechanism, in which the product design is the design focus and the parameters for the workstation and process design remain the same for all design solutions. In this case, the workstation is based on the *Concept Laser Mlab*, which is consistent with the workstation designed for the holder design case, and the process parameters also adopt the fast build strategy employed in the holder case.

### 7.1.2 Topology optimization of the cam plate

Based on the use scenario, two mechanical load cases are defined: First, when a cylindrical rod falls on the cam plate, the impact force is approximately 750 N maximum. By considering a factor of two, axial forces of 1,500 N pointing to the center of the cam plate are assumed, as depicted in load case 1 in Figure 7-1. Second, the rod is conveyed by the cam plate, leading to a tangential force of 600 N. In the center of the cam plate, fixed support is defined because it is connected to a shaft, as depicted in load case 2 in Figure 7-1.

For the optimization of the cam plate, the same approach as in the design case of the holder is applied, in which the ratio of volume reduction ($\alpha$ in Figure 7-1) has been varied from 0.01 to 0.7. For each $\alpha$ value, an optimization is performed and a new geometry is created, and the maximum stress and distortion ($\sigma_{max}$ and $\varepsilon_{max}$) values are summarized in Table 7-1. Considering that the calculated safety factors for all design solutions are greater than 3, it can be concluded that all of the optimized geometries are feasible for functional use and should be considered in the energy performance assessment.

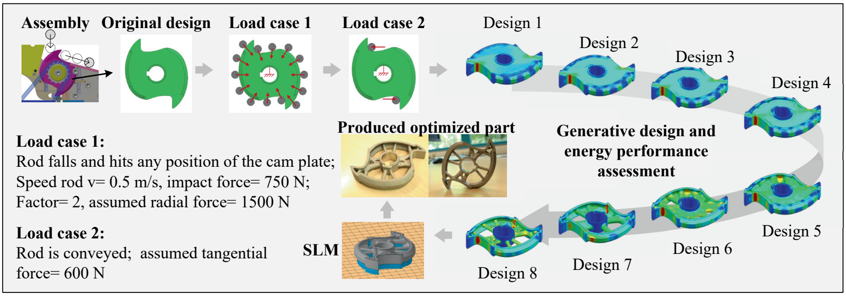



Figure 7-1: Design solutions for the product optimization of the cam plate

### 7.1.3 EnPI-based assessment of the optimized cam plate

Following the topology optimization, the energy simulations are conducted. Five EnPIs are defined for the energy performance assessment, of which three are the same EnPIs used in the design case of the holder (TEC, SFER, and EC). The other two EnPIs are the volume-TEC (VTEC) coefficient and distortion-TEC (DTEC) coefficient. The VTEC describes the inverse of the product of the volume ($V_1$) and total energy consumption (TEC), and it is defined as follows:

$$VTEC = \frac{1}{TEC \times V_1}$$ Equation 7-1

When evaluating VTEC, a higher value implies superior energy performance; hence, the general approach to enlarging VTEC is reducing either $V_1$ or TEC. The DTEC describes the inverse of the product of the maximum distortion as indicated by FEA ($\varepsilon_{max}$) and TEC, and it is expressed as follows:

$$DTEC = \frac{1}{TEC \times \varepsilon_{max}}$$ Equation 7-2

The evaluation of DTEC follows a similar principle to the evaluation of VTEC in that higher values imply better ratings. Therefore, the general approach to enlarging DTEC is reducing either TEC or $\varepsilon_{max}$. Table 7-1 presents the calculated original EnPI values.

| Design solutions and simulation result | | | | | | | Original EnPI | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | α | $V_1$ (cm³) | $m_1$ (g) | $\sigma_{max}$ (MPa) | $\varepsilon_{max}$ (mm) | Safty factor | TEC (MJ) | VTEC (1/(MJ*cm³)) | SFER (1/MJ) | DTEC (1/(mm*MJ)) | EC(€) |
| 1 | 0.01 | 55.054 | 443.185 | 40.160 | 0.004 | 9.587 | 6.53E+01 | 2.78E-04 | 1.47E-01 | 3.52E+00 | 3.45E+00 |
| 2 | 0.1 | 51.204 | 412.192 | 40.240 | 0.004 | 9.568 | 6.35E+01 | 3.08E-04 | 1.51E-01 | 3.64E+00 | 3.35E+00 |
| 3 | 0.2 | 46.461 | 374.011 | 40.430 | 0.004 | 9.523 | 6.35E+01 | 3.39E-04 | 1.50E-01 | 3.62E+00 | 3.35E+00 |
| 4 | 0.3 | 41.318 | 332.610 | 40.620 | 0.005 | 9.478 | 6.29E+01 | 3.85E-04 | 1.51E-01 | 3.48E+00 | 3.32E+00 |
| 5 | 0.4 | 35.551 | 286.186 | 41.300 | 0.005 | 9.322 | 6.18E+01 | 4.55E-04 | 1.51E-01 | 3.17E+00 | 3.26E+00 |
| 6 | 0.5 | 29.320 | 236.026 | 48.700 | 0.005 | 7.906 | 6.08E+01 | 5.61E-04 | 1.30E-01 | 3.01E+00 | 3.21E+00 |
| 7 | 0.6 | 23.138 | 186.261 | 100.900 | 0.013 | 3.816 | 5.53E+01 | 7.82E-04 | 6.90E-02 | 1.36E+00 | 2.92E+00 |
| 8 | 0.7 | 19.782 | 159.245 | 109.200 | 0.022 | 3.526 | 5.47E+01 | 9.24E-04 | 6.44E-02 | 8.45E-01 | 2.89E+00 |

Table 7-1: Simulation results and calculated original EnPIs

The normalized and aggregated EnPI values are summarized and visualized in Figure 7-2. From both stacked area charts, it can be seen that design solution 8 scores the highest after both normalization and aggregation, as approximately 70% of the intended volume reduction is achieved. Moreover, another finding is that the area of DTEC is reduced from the normalization to the aggregation. The reason for this reduction is that DTEC is considered to have a low priority level, as the distortions of the cam plate under different design conditions are on the µm level and not critical for actual use. Finally, design solution 8 is selected as the best solution, and the optimized part is produced using SLM, as shown in Figure 7-1.

**A) Calculation of weighting factors (WF)**

| EnPI | Priority | EnPI | | | | | Score | WF |
|---|---|---|---|---|---|---|---|---|
| | | TEC | VTEC | SFER | DTEC | EC | | |
| TEC | High | | 6 | 6 | 6 | 6 | 24 | 0.358 |
| VEC | Middle | 1 | | 3 | 6 | 3 | 13 | 0.194 |
| SFER | Middle | 1 | 3 | | 6 | 3 | 13 | 0.194 |
| DTEC | Low | 1 | 1 | 1 | | 1 | 4 | 0.060 |
| EC | Middle | 1 | 3 | 3 | 6 | | 13 | 0.194 |

**B) Calculation of normalized EnPI´**

| Design No. | TEC | VTEC | SFER | DTEC | EC | Sum |
|---|---|---|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.95 | 0.96 | 0.00 | 1.91 |
| 2 | 0.17 | 0.05 | 1.00 | 1.00 | 0.17 | 2.38 |
| 3 | 0.17 | 0.09 | 0.99 | 0.99 | 0.17 | 2.42 |
| 4 | 0.22 | 0.16 | 1.00 | 0.94 | 0.22 | 2.55 |
| 5 | 0.33 | 0.27 | 1.00 | 0.83 | 0.33 | 2.77 |
| 6 | 0.42 | 0.44 | 0.76 | 0.77 | 0.42 | 2.81 |
| 7 | 0.95 | 0.78 | 0.05 | 0.19 | 0.95 | 2.92 |
| 8 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 3.00 |

**C) Calculation of aggregated EnPI´´**

| Design No. | TEC | VTEC | SFER | DTEC | EC | Sum |
|---|---|---|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.19 | 0.06 | 0.00 | 0.24 |
| 2 | 0.06 | 0.01 | 0.19 | 0.06 | 0.03 | 0.36 |
| 3 | 0.06 | 0.02 | 0.19 | 0.06 | 0.03 | 0.36 |
| 4 | 0.08 | 0.03 | 0.19 | 0.06 | 0.04 | 0.41 |
| 5 | 0.12 | 0.05 | 0.19 | 0.05 | 0.06 | 0.48 |
| 6 | 0.15 | 0.08 | 0.15 | 0.05 | 0.08 | 0.51 |
| 7 | 0.34 | 0.15 | 0.01 | 0.01 | 0.18 | 0.70 |
| 8 | 0.36 | 0.19 | 0.00 | 0.00 | 0.19 | 0.75 |

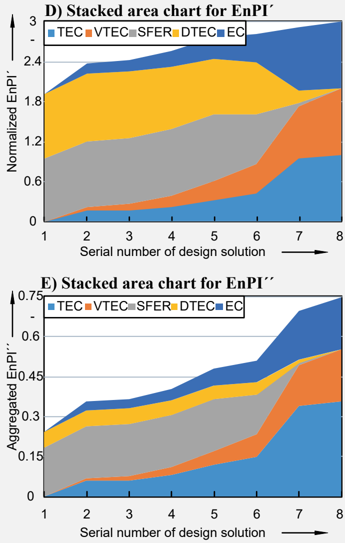



Figure 7-2: Normalized and aggregated EnPIs for the optimization of the cam plate

Moreover, it is worth noting that the machine used for the production is the SLM 500, which is not the reference system used for the energy simulation (the *Concept Laser Mlab*). The reason for the choice of the SLM 500 is that the maximum size of the build platform for the Concept Laser Mlab is only 90 x 90 mm², while the outer diameter of the cam plate is approximately 100 mm. However, in this use case, the energy performance assessment only considers the effect of changing the product design and disregards the impacts of AM systems. Therefore, although the real energy consumption may differ from the simulated energy consumption, the decision made based on the energy performance assessment will still be valid. It is only in cases in which the system-related design parameters are varied that the impact of AM systems should be considered during the energy performance assessment, and the AM system used in the energy simulation should be consistent with the AM system used for production.

## 7.2 Use case 2: Build orientation design for producing a lattice ring

### 7.2.1 Situation analysis of the lattice ring

In the second use case, the design objective is to determine the optimal build orientation for producing a lattice ring with respect to energy performance. Figure 7-3 shows the design of the lattice ring, the outer and inner diameters of which are 22 mm and 19.5 mm, respectively. The outer side of the ring features a lattice structure consisting of numerous lattice units with a rod diameter of 0.03 mm and a rod length of 1.2 mm. This design case implies a process-related design mechanism, meaning that the product design and workstation design remain the same for all design solutions.

### 7.2.2 Build process design of lattice ring

By varying the angle between the circle surface of the ring and the build platform, the build orientation of the ring can be changed to propose different design solutions, as shown in Figure 7-3. It can be seen that the change of the build orientation has a significant impact on the distribution of thermal stress as well as distortion. From the thermal-structural simulation, it is concluded that the maximum stress and distortion occur when the orientation angle is 60°, while the minimum stress and distortion occur when the angle is set to 0°.

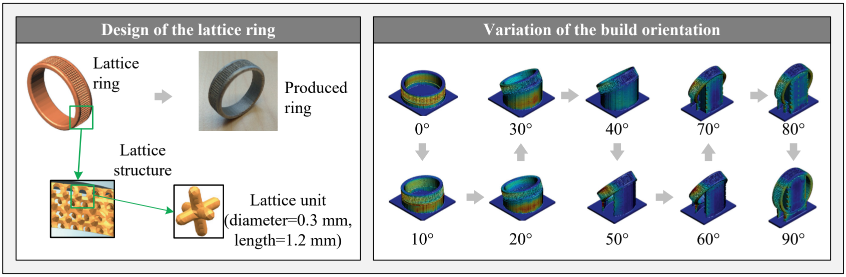



Figure 7-3: Design case of the lattice ring

### 7.2.3 EnPI-based assessment of different build orientation solutions

Since this use case focuses on the process design, the EnPIs that indicate aspects of product performance such as the safety factor-TEC ratio (SFER) or SEC, are not used. In this use case, the energy performance assessment considers only two original EnPIs, as shown in Table 7-2. The first is the total energy consumption (TEC), while the second is the displacement ($\varepsilon_{max}$) of the build process, which is obtained from the thermal-structural simulation.

In this use case, both EnPIs show the same importance; hence, the weighting factor of 0.5 is defined for both. Subsequently, the aggregated EnPI″ is the product of 0.5 with the sum of the normalized $\varepsilon_{max}'$ and TEC′, and it is given by the following equation:

$$EnPI'' = 0.5(\varepsilon_{max}' + TEC') \quad \text{Equation 7-3}$$

| No. | Orientation (°) | Original EnPI | | Normalized EnPI' | | Aggregated EnPI'' |
|---|---|---|---|---|---|---|
| | | $\varepsilon_{max}$ (µm) | TEC (kJ) | $\varepsilon_{max}$' | TEC' | |
| 1 | 0 | 65.8 | 3.31E+03 | 1.00 | 1.00 | 1.00 |
| 2 | 10 | 68.2 | 3.60E+03 | 0.98 | 0.86 | 0.92 |
| 3 | 20 | 73.8 | 3.91E+03 | 0.94 | 0.70 | 0.82 |
| 4 | 30 | 92.3 | 4.30E+03 | 0.80 | 0.51 | 0.66 |
| 5 | 40 | 155 | 4.71E+03 | 0.33 | 0.32 | 0.32 |
| 6 | 50 | 192 | 4.86E+03 | 0.05 | 0.24 | 0.15 |
| 7 | 60 | 199 | 5.18E+03 | 0.00 | 0.08 | 0.04 |
| 8 | 70 | 101 | 5.24E+03 | 0.74 | 0.06 | 0.40 |
| 9 | 80 | 91.1 | 5.31E+03 | 0.81 | 0.03 | 0.42 |
| 10 | 90 | 103 | 5.36E+03 | 0.72 | 0.00 | 0.36 |

Table 7-2: Quantification of EnPIs for the design solutions of the lattice ring

The normalized and aggregated EnPIs are summarized in Table 7-2 and visualized in Figure 7-4. From Figure 7-4, it can be seen that design solution 1 scores the highest for both normalized and aggregated EnPIs, followed by solutions 2 and 3. These results indicate that the best build orientation is to set the angle between the ring and the platform at 0°.

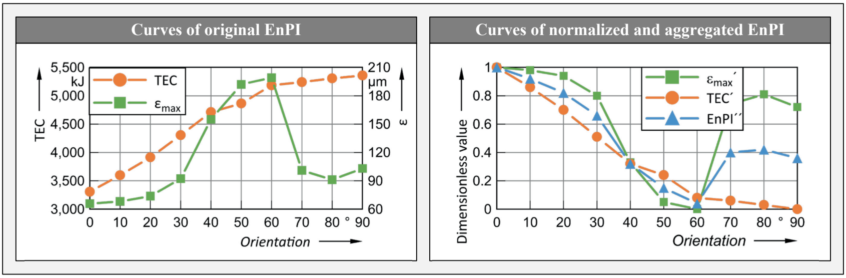



Figure 7-4: Curves of the calculated EnPI

## 7.3 Use case 3: Build process design of a bottle opener regarding build cost and energy performance

### 7.3.1 Situation analysis of the opener

The third use case involves combining the energy performance assessment and the cost estimation for determining the optimum process design for producing a bottle opener. Compared to the previous design cases, in which only single parts were considered, this use case considers the production of multiple parts during one build task. The AM workstation is the same as that used for the design case of the holder.

### 7.3.2 Topology optimization and build process design of the opener

Although this use case also involves the application of topology optimization to make the product more suitable for AM, the product design remains the same for all design solutions; hence, the use case implies the process-related design mechanism, and the design focus is on the process design.

In topology optimization, a weight reduction of 45% is achieved. For the process design, the build orientation and number of parts are considered; the design solutions are depicted in Figure 7-5. In solutions 1 to 5, the opener is built in the "standing" position, and the number of parts increases from one to nine. In the remaining four design solutions, the opener is produced in the "lying down" position, and the number of parts increases from one to seven. Due to the change in the build orientation, the support structure and the number of layers change, and these changes will eventually result in different levels of energy performance.

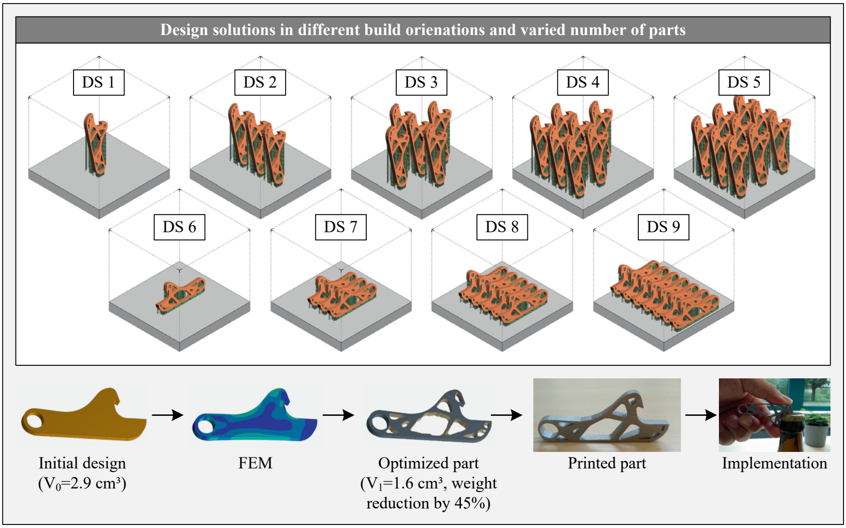



Figure 7-5: Design solutions for the bottle opener

### 7.3.3 EnPI-based assessment combined with cost estimation

Similarly to the use case of the lattice ring, this use case focuses on the process design and considers the impact of changes in build orientation. Thus, the maximum displacement ($\varepsilon_{max}$) from the thermal-structural simulation of the build process is defined as the first EnPI. The second EnPI is the energy consumption per piece (EP), which is the ratio between the total energy consumption (TEC) and the number of parts (n), as defined below:

$$EP = \frac{TEC}{n} \qquad \text{Equation 7-4}$$

For the aggregation, the weighting factors for both EnPIs are defined as 0.5; hence, the aggregated EnPI″ is the product of 0.5 with the sum of the normalized $\varepsilon_{max}'$ and EP′, and it is expressed as follows:

$$EnPI'' = 0.5({\varepsilon_{max}}' + EP') \qquad \text{Equation 7-5}$$

Table 7-3 summarizes the results of the calculation, normalization, and aggregation of both EnPIs. Based on the evaluation of $\varepsilon_{max}$, it can be seen that the displacement of the solutions with the orientation "standing" (solution 1 to 5) is lower than that of the solutions with the orientation "lying down" (solution 6 to 9), which suggests that "standing" is a better build orientation.

Based on the evaluation of EP, it is concluded that a higher number of parts leads to lower EP values. The reason for this is that, for the build with multiple parts, the fixed energy consumption can be amortized by the inclusion of more parts. For example, solutions 1 and 5 have the same number of layers (1,068 layers), as the heights of parts and predefined layer thickness (25 µm) for both solutions are the same. Consequently, both solutions have the same number of scanning loops and the same fixed energy use of the servos used for build platform leveling and powder spreading. However, in solution 1, the fixed energy use is allocated to a single part, while, in solution 5, the fixed energy use is amortized by nine parts. Therefore, the EP in solution 5 is lower than in solution 1.

| Energy performance assessment | | | | | | | Cost estimation | |
|---|---|---|---|---|---|---|---|---|
| **Design No.** | **TEC (kJ)** | **EP (kJ/piece)** | **$\varepsilon_{max}$ (µm)** | **EP'** | **$\varepsilon_{max}'$** | **EnPI''** | **Cost (€)** | **Cost per piece (€)** |
| 1 | 1.21E+04 | 1.21E+04 | 263 | 0.00 | 1.00 | 0.50 | 47.87 | 47.87 |
| 2 | 1.70E+04 | 5.66E+03 | 289 | 0.79 | 0.76 | 0.78 | 62.73 | 20.91 |
| 3 | 2.74E+04 | 5.47E+03 | 297 | 0.82 | 0.69 | 0.75 | 93.93 | 18.79 |
| 4 | 3.41E+04 | 4.88E+03 | 293 | 0.89 | 0.72 | 0.81 | 114.36 | 16.34 |
| 5 | 4.17E+04 | 4.63E+03 | 298 | 0.92 | 0.68 | 0.80 | 139.01 | 15.45 |
| 6 | 6.62E+03 | 6.62E+03 | 363 | 0.67 | 0.07 | 0.37 | 24.58 | 24.58 |
| 7 | 1.42E+04 | 4.74E+03 | 365 | 0.91 | 0.06 | 0.48 | 47.67 | 15.89 |
| 8 | 2.09E+04 | 4.19E+03 | 365 | 0.97 | 0.06 | 0.52 | 67.92 | 13.58 |
| 9 | 2.79E+04 | 3.98E+03 | 371 | 1.00 | 0.00 | 0.50 | 89.75 | 12.82 |

Table 7-3: Calculation of EnPIs and build cost

The aggregated EnPI″ are visualized together with the estimated build costs in the form of a point chart (see Figure 7-6). The general rule for evaluating the combined build cost and energy performance is to identify design solutions with higher EnPI″ values and lower cost values. Therefore, the solutions located in the bottom right of the point chart indicate better performances with lower build costs. Based on the evaluation of the EnPI″ values, solution 4 scores the highest (0.81), followed by solution 5 (0.8). Since the difference between the scores of solutions 4 and 5 is negligible, it can be seen that the energy performances of solutions 4 and 5 are equivalent. Moreover, given that the build cost of solution 5 is approximately 1 € lower than that of solution 4, solution 5 should be selected as the optimum design solution.

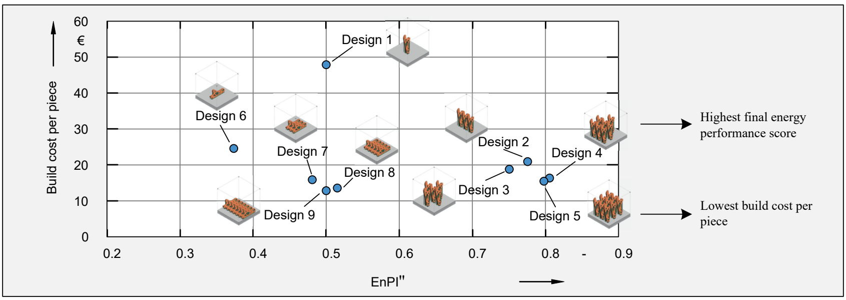



Figure 7-6: Point chart of the build cost and energy performance per piece

# 8 Summary and Outlook

AM is considered to be cleaner than conventional manufacturing, and its environmental benefits include, for example, the resource savings that can be achieved through lightweighting, the shortening of process chains, and innovation in terms of sustainable business models. However, recent studies have also indicated that the environmental performance of AM can be worse than that of conventional manufacturing in different life stages and application scenarios. Therefore, the environmental performance of AM should be evaluated in the design phase, and the environmental benefits of AM should be validated using eco-design methods.

Today, eco-design for AM approaches focus on the use of LCA, in which process chains are mapped with respect to predefined functional units and system boundaries. Based on the inventory and lifecycle impact analyses, the environmental performance of AM can be expressed in the form of equivalent impact indicators, and AM-related design solutions can be further evaluated and compared with the same baseline. However, LCA requires the full process chain model and detailed inventory data; therefore, LCA can only be performed after the design process or must be integrated into the later design stage. This may result in repeated design and evaluation activities, which can lead to waste in terms of both time and cost. To enable a better integration of design and evaluation, an energy performance assessment can be used to replace LCA as the evaluation tool in the middle design stage of eco-design for AM, as such an assessment requires neither a full process chain model nor detailed inventory data. However, no existing study has integrated an energy performance assessment into an eco-design for AM approach. By aiming to address this research gap, this dissertation contributes by presenting a holistic framework intended to enable the eco-design for AM based on energy performance quantification and assessment. In the following, the content of the proposed framework is first briefly summarized, after which possibilities in terms of future work are described.

**Summary of the framework**

The research objective of this dissertation is to develop and validate a holistic concept for the implementation of eco-design for AM featuring an energy performance assessment. The proposed framework consists of the following three parts:

First, based on the modeling of the energy flows of two representative AM systems, a simulation tool is developed in which the *NC code and database-driven approach* is applied using the MATLAB/Simulink platform. For the simulation, users need to finish the process design and generate an NC code for the designed build process. Thereafter, the time parameters of the NC code are extracted and integrated with the power data of system components stored in a predefined database into energy values. With the simulation tool, designers can conveniently predict the energy demand of a build process in seconds. Moreover, to verify the simulation accuracy and reliability, experiments are performed, and the results thereof are compared with those of simulations.

Second, to enable the energy performance assessment of AM, an EnPI-based multiple-dimensional assessment model is proposed. This model consists of the following three levels:

- **Level I: Original EnPIs:** The first level comprises the EnPIs that can be directly quantified from the AM processes based on experiments or simulations. According to the units used, the original EnPIs can be classified as energy values, ratios of energy values, combinations of energy and non-energy values, and non-energy unit but related values.

- **Level II: Normalized EnPIs:** The second level contains normalized EnPI values. Since multiple original EnPIs have different units and cannot be compared directly, this assessment model suggests using a *min-max scaling* approach to scale the values of original EnPI into dimensionless values ranging from 0 to 1.
- **Level III: Aggregated EnPIs:** The third level describes the aggregation of normalized EnPIs with weighting factors. To calculate the weighting factors, the *pairwise comparison* approach has been used. The sum of the aggregated EnPI values for a design solution represents the final energy performance of the case.

Third, based on the proposed simulation tool and assessment model, a method for eco-design for AM is proposed, in which the following five phases are described:

- **Phase 1: Situation analysis:** In the first phase, the use scenario and the requirements are first specified and the functional and geometric features of the existing product are described. Thereafter, production scenario with conventional manufacturing is described and documented. Finally, AM processes that can be used for the design case are specified and compared with the conventional production scenario from the economic and technical perspectives.
- **Phase 2: Topology optimization**: The second phase describes the product design for AM processes, in which topology optimization is applied. For the optimization, the design space and mechanical boundary conditions of the product are defined based on the application scenario. Subsequently, FEA and lightweighting are performed with specified optimization goals (e.g., desired mass reduction).
- **Phase 3: AM workstation design:** In the third phase, an AM workstation for performing the build task of the optimized product should be designed. For this purpose, the peripheral units related to the use of selected AM machines are defined according to the necessary operations at the workstation level. Thereafter, the location of the AM workstation and the workstation layout are defined.
- **Phase 4: Build process design**. In the fourth phase, the build process is defined, in which process parameters such as layer thickness and build orientation are decided and the process performance is evaluated using a thermal-structural simulation. Thereafter, any post-processing steps that may be required to improve the surface finishing and geometrical accuracy of the AM components are defined.
- **Phase 5: EnPI-based assessment**. In the final phase, the respective energy consumptions of the design solutions are predicted using the proposed simulation tool. Thereafter, the EnPIs are defined according to the design requirements in the situation analysis. For all design solutions, the defined EnPIs are quantified, normalized, weighted, and aggregated according to the assessment model. Finally, through the evaluation and comparison of the EnPI, the optimum design solution is selected.

To validate the feasibility of the framework, it has been applied to three use cases. Based on the results of these cases, it is concluded that the proposed framework is a convenient and efficient tool with which to develop, evaluate, and select an optimum design solution based on the energy performance of AM.

**Future work**

With respect to the future application and extension of the framework presented in this dissertation, the following issues should be addressed:

- **Extension of the power database:** In this dissertation, the database of the simulation tool only contains the power data of two AM systems. However, the simulation logic and software architecture have already been described, and the possibility of extending the database has been identified. Therefore, the first possibility in terms of future work could be the acquisition and integration of power data for different AM systems into the power database.
- **Exploration of additional EnPIs:** In eco-design for AM, EnPI should be defined according to the specific requirements of a design purpose. Therefore, another area of future work could be the exploration of additional possible EnPIs for dealing with individual design cases.
- **Transfer and standardization of the framework:** Last but not least, in the future, it is suggested that production companies interested in AM technologies apply and standardize the proposed framework within their companies or production networks. The cumulative environmental benefits achieved by individual companies through the adoption of the framework will eventually lead to an environmental improvement across the entire manufacturing industry.

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# 10 Appendix

## 10.1 Appendix A: A brief introduction to bond graph

In modeling physical systems, graphical representation of system models is always more suitable for human perception than an oral or textual representation [Boru10]. Compared to other graphic modeling approaches like block diagrams or signal flow diagrams, a bond graph applies a bond to indicate a power flowing from a system to another. Bond graphs follow the hypothesis that the power (*p*) can be expressed as the product of an effort variable (*e*) and a flow variable (*f*); it is expressed in the following equation [Payn61]:

$$p = e \times f \qquad \text{Equation 10-1}$$

In different energy domains, the interpretation of the effort and flow variable is different. For example, in the electric domain, effort and flow are voltage and current, respectively, while in translational mechanics, the effort is force and flow is velocity. Table 10-1 summarizes the effort and flow variables in different energy domains.

| Energy domain | Effort | Flow |
|---|---|---|
| Mechanical translational | Force | Velocity |
| Mechanical rotational | Torque | Angular velocity |
| Electro-magnetic | Voltage | Current |
| | Magneto motive force | Magnetic flux rate |
| Hydraulic | Total pressure | Volume flow |
| Thermodynamic | Temperature | Entropy flow |
| Chemical | Chemical potential | Molar flow |

Table 10-1: Effort and flow variables in different energy domains [Boru10]

In bond graph, the places, where systems can be connected, and power can flow between them, are called *ports* [Karn12]. The systems with those ports are called *multiports*. According to the number of ports, a system with one port is called *1-port* element, and a system with *n* ports is called *n-port* element. For example, batteries are usually 1-port elements because they can only output energy, and electric motors are 2-port elements, since they first consume electricity from a battery or grid (input port) and then transform the electricity to the rotational movement (output port). In the terminology of the bond graph, the fundamental multiports are effort source (Se), flow source (Sf), inductor (I), capacitor (C), resistor (R), transformer (TF), gyrator (GY), 0-junction, and 1-junction. The general structure of a bond graph is shown in Figure 10-1. Between any two multiports, the power flow is represented in a bond with half arrow. For more information about the port elements, please refer to [Karn12, Boru10].

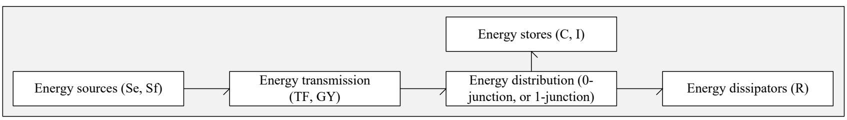


Figure 10-1: General structure of a bond graph

Table 10-2 summarizes the symbols and preferred causalities of multiports. The causality is indicated by a perpendicular stroke on a bond, representing the direction of effort signal [Boru10]. Note that the signal direction of an effort is not always the same to the direction of a power flow. For example, the element Se provides constant effort, and the causality stroke should be added to the side with the arrow, and its direction is consistent with the direction of power flow, while the element Sf provides constant flow, and the causality stroke should be added to the side without the arrow, implying the direction of effort signal is different with the direction of the power flow. Moreover, it is to mention that at the 0-junction, all power bonds share the same effort, and only one effort is allowed to be an input. Therefore, only one causality stroke is allowed on the bond into the 0-junction. Conversely, for the 1-junction, all efforts except one must be the input to the 1-junction; hence, only one power bond on the 1-junction is allowed to have the causality stroke on the outside of the bonds connected with the 1-junction.

| Elements | Symbols and preferred causality |
|---|---|
| Effort source | Se ⇁\| |
| Flow source | Sf \|⇁ |
| Inductor | I \|↼ |
| Capacitor | C ↽\| |
| Resistor | R ↽\|, or R \|↼ |
| Transformer | \|↼TF\|↼ , or ↽\|TF↽\| |
| Gyrator | \|↼GY↽\| , or ↽\|GY\|↼ |
| 0-junction | ↿̄<br>⇁\| 0 ⇁\| |
| 1-junction | ↿̲<br>\|⇁ 1 \|⇁ |

Table 10-2: Symbols and preferred causality of multiports [Boru10]

The bond graph, in which the power is the product of effort and flow variables, is also called a true bond graph. In the thermodynamic and hydraulic domain, a pseudo bond graph is also applied to model the power exchange of thermal fluid systems [Boru10, Thom75]. In a pseudo bond graph, the effort and flow variables are pressure and mass flow for representing hydraulic, and temperature and heat flow or enthalpy flow for representing thermal power. For more information about the pseudo bond graph, please refer to [Thom00].

## 10.2 Appendix B: Bond graph for Concept Laser Mlab

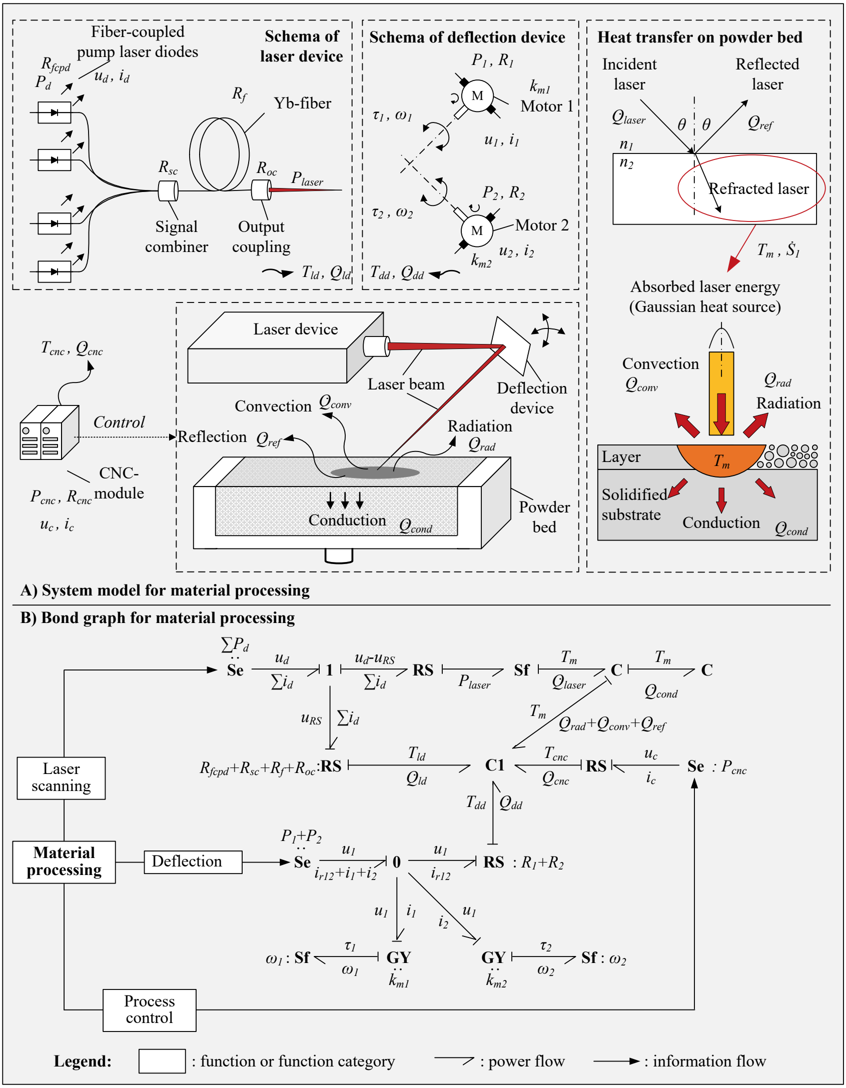


Figure 10-2: Bond graph for material processing

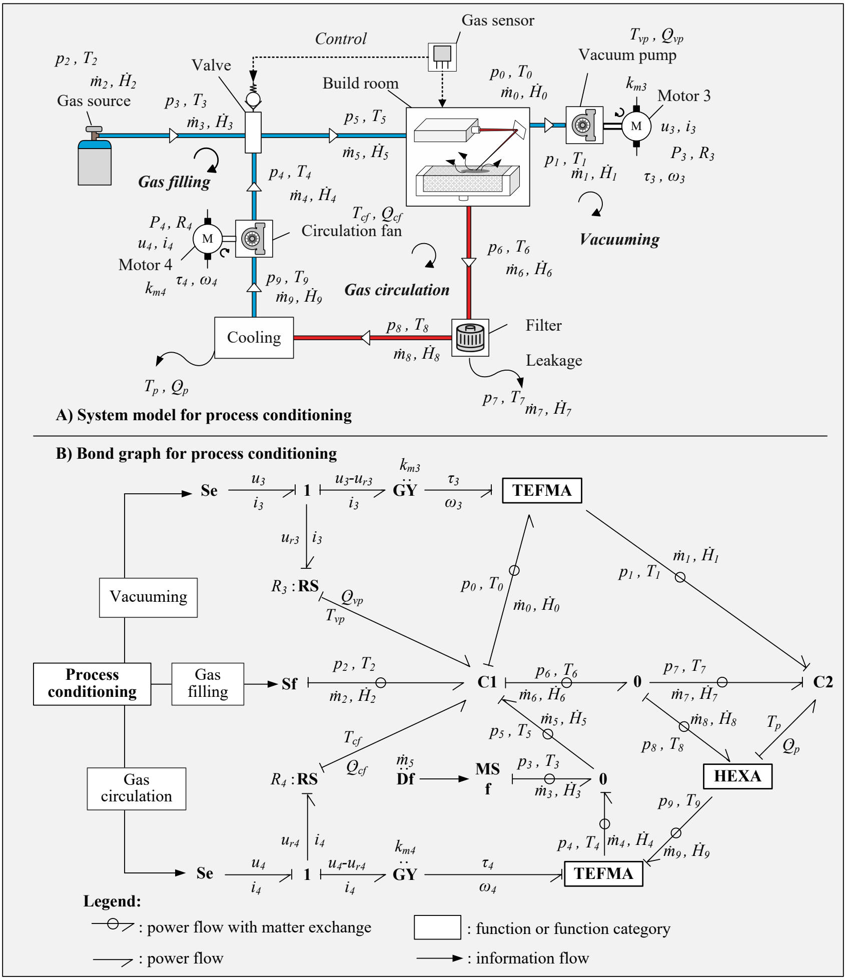


Figure 10-3: Bond graph for process conditioning

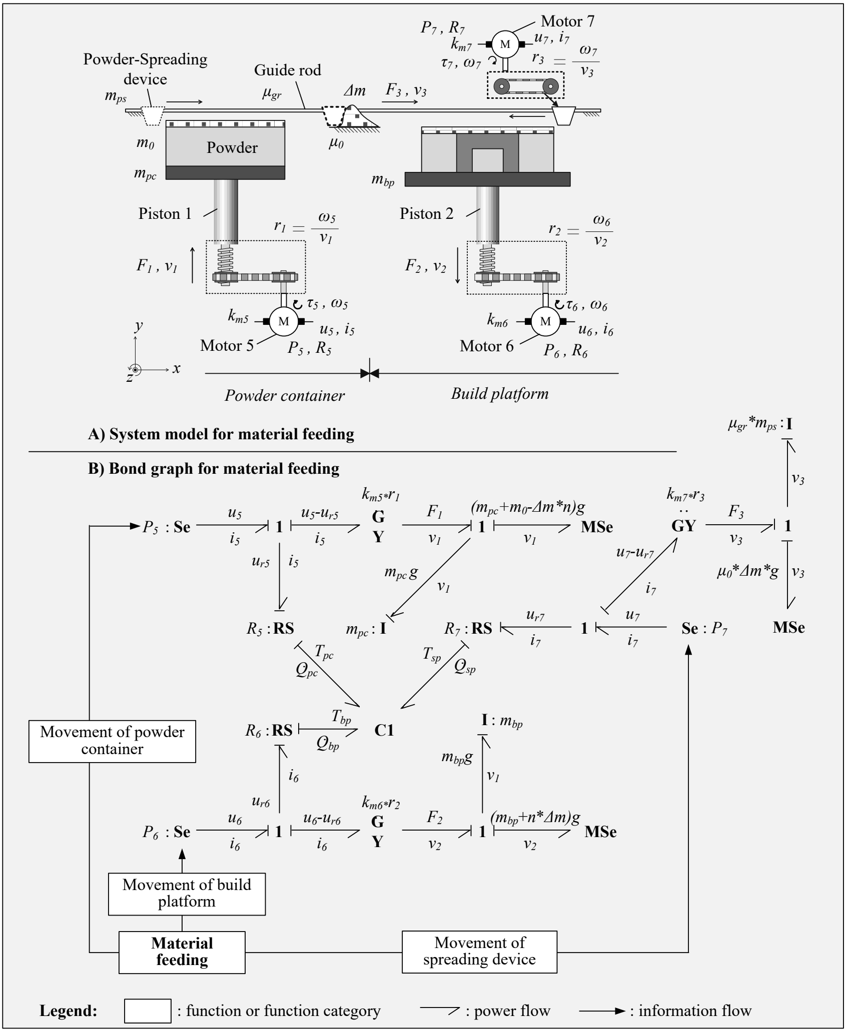


Figure 10-4: Bond graph for material feeding

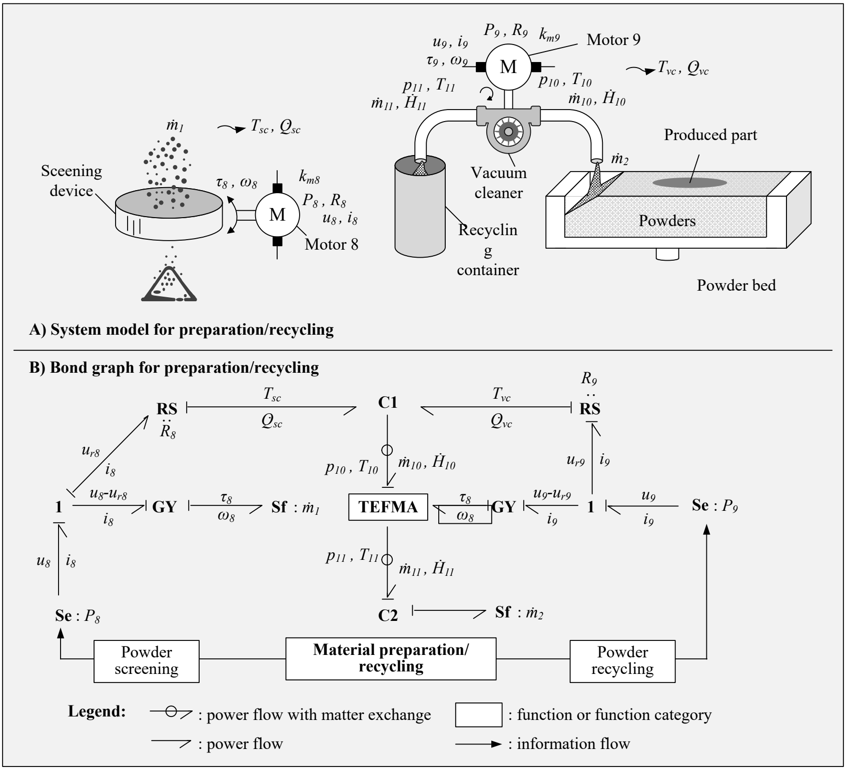


Figure 10-5: Bond graph for material preparation/recycling

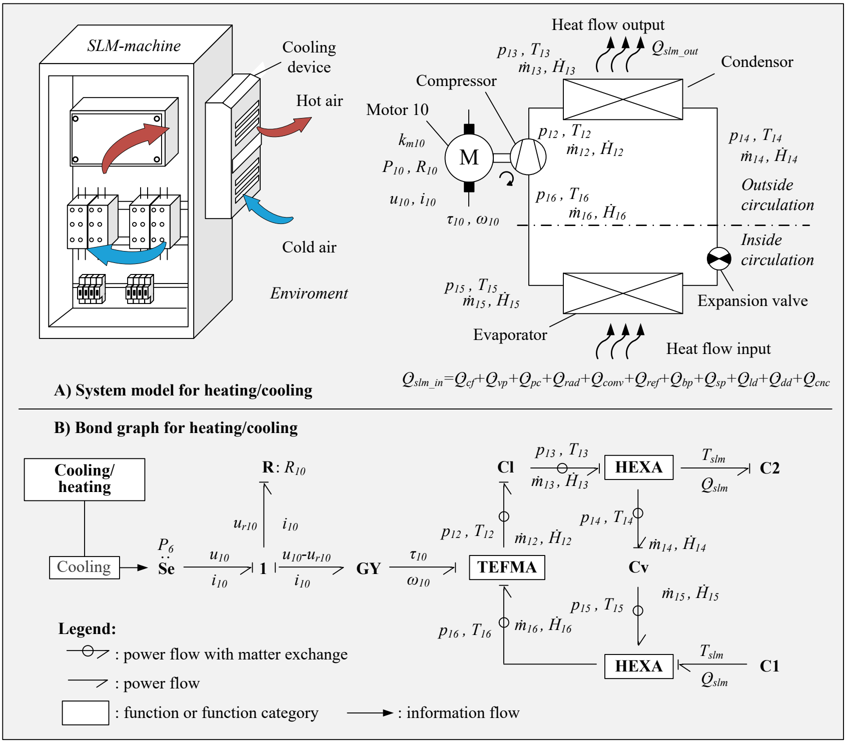


Figure 10-6: Bond graph for heating/cooling

## 10.3 Appendix C: Bond graph for Ultimaker 3

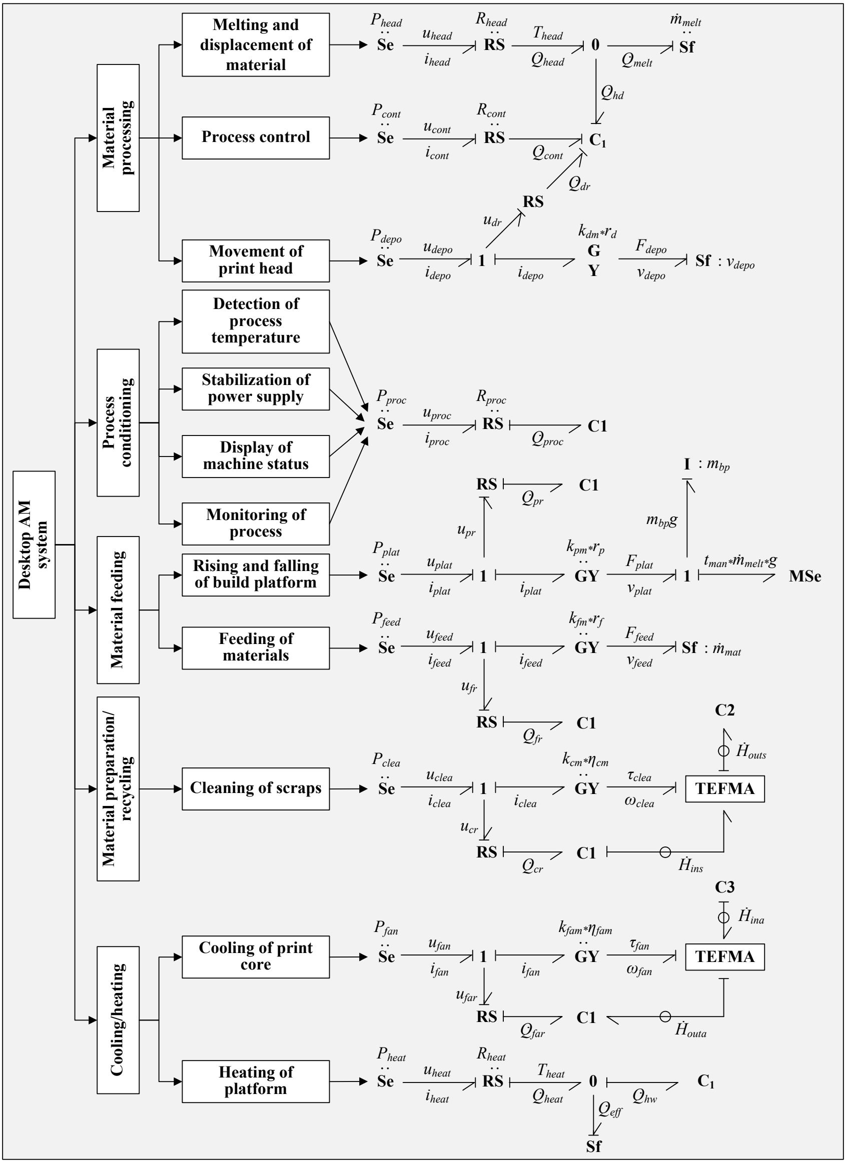


Figure 10-7: Bond graph for Ultimaker 3

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