Heliyon 10 (2024) e25706

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Selective laser melting: Evaluation of the effectiveness and reliability of multi-scale multiphysics simulation environments

Thierry Abedi Mukalay *, John Alfred Trimble, Khumbulani Mpofu, Rumbidzai Muvunzi

Department of Industrial Engineering, Faculty of Engineering and Building of the Environment, Tshwane University of Technology, Pretoria, 0183, South Africa

ARTICLE INFO

Keywords:
Simulation modelling
SWOT analysis
ANP
Multi-scale multiphysics
Simulation environment

ABSTRACT

This study evaluates the effectiveness and reliability of Multi-scale Multiphysics Selective Laser Melting (SLM) Simulation Environments. A literature review and bibliometric analysis were conducted to identify the most widely used SLM Simulation Environments. The effectiveness of simulation environments was assessed through a SWOT analysis enhanced by an Analytic Network Process (ANP). The reliability of simulation environments was analysed through a design of experiment (DoE). The DoE solely assessed the ability of these environments to accurately predict part distortion. The results showed that the most robust SLM process simulation modelling systems are Ansys Additive Print, Comsol, Simufact Additive, Netfabb, and Simulia.

1. Introduction

Yin and McKay [1] described simulation modelling as handling input data and analysing the output, and Seekhao et al. [2] described designing a conceptual system model and using it to run experiments to understand its behaviour. Simulating engineering systems employs two different modelling methods: mechanism simulation, whose performance is governed by physical laws and process simulation, which is governed by humans, groups, and organisational behaviours [2]. This study focuses on the mechanisms of simulation modelling environments.

SLM is a transformative emerging technology that offers unlimited aesthetic freedom and environmental benefits, particularly for fabricating metal parts with complex geometries [3]. However, since SLM involves intricate processes with numerous uncertainties, the quality of the final product often exhibits substantial variations [4], which makes it very difficult to produce parts of high and consistent quality and, therefore, to gain widespread acceptance of the technology. In this sense, it is unsurprising that experts study ways to improve SLM processes to achieve greater repeatability and reliability. Producing successful SLM components requires comprehensive knowledge of design and manufacturing processes. For example, metal parts can be distorted due to residual stresses or have poor mechanical properties due to porosity. Traditionally, to achieve a reliable, repeatable process, trial and error have been adopted. However, this often changes the printing parameters several times before success is achieved, thus leading to considerable expense and loss of time [5].

In contrast, a computer-based simulation approach based on comprehensive physical principles is increasingly popular as an

* Corresponding author.
E-mail addresses: thie7ry@gmail.com, 217632501@tut4life.ac.za (T.A. Mukalay), trimbleja@tut.ac.za (J.A. Trimble), MpofuK@tut.ac.za (K. Mpofu), MuvunziR@tut.ac.za (R. Muvunzi).

https://doi.org/10.1016/j.heliyon.2024.e25706
Received 28 July 2023; Received in revised form 31 January 2024; Accepted 31 January 2024
Available online 8 February 2024

alternative to trial and error. Simulations can help further enhance SLM processes by allowing consistency and better-quality parts. Lindgren et al. [6] stated that simulation models may be key to improving SLM part quality and repeatability. By evaluating the performance and design of parts, simulation modelling can prevent the development of defective prints. Simulation can determine the impact of key process variables on the result, such as print orientation, laser power, laser speed, and support location.

Moreover, simulation can help to reduce the possibility of part deformation and make fabrication more repeatable, as well as eliminate material waste caused by defective prints, thereby reducing the cost of manufacturing [6]. In light of the above, it is essential to evaluate the strengths, weaknesses, opportunities, and threats of leading simulation environments to assess their potential and suitability for specific applications, having in mind the technological advances made in the field of SLM modelling and various simulation environments created in the last few years. Several studies conducted in additive manufacturing simulation have demonstrated that an effective additive manufacturing tool's critical capabilities are Modelling and Simulation, Design, Materials, Build Process, and Post-processing [7]. These capabilities are discussed further in the study.

This study aims to develop a SWOT analysis of SLM Simulation Environments based on a comprehensive literature review and bibliometric analysis of recent studies on the subject, coupled with a DoE, to evaluate the reliability of simulation tools to accurately predict part distortion levels. As there is no systematic mechanism to quantify the performance of assessing factors in a SWOT analysis, this study implements Quezada et al.'s [8] multicriterial decision-making model to improve priority ranking and performance measurement within the analysis through an ANP. This paper adds to the literature on comparative reviews of simulation modelling in additive manufacturing technology. The study follows a six-part structure: Data, Methods, Results, Discussion, Conclusion, and Future Research.

2. Data

2.1. Study area

Despite the diversity of simulation modelling tools, this paper focuses exclusively on environments that allow simultaneous multi-scale and Multiphysics modelling. Multi-scale modelling refers to a system definition using several models at different scales. Different resolutions are used in several models, such as macroscale or microscale. Due to the insufficient precision of available macroscale models and the lack of efficiency of microscale models, multi-scale modelling is necessary. Combining both scales can result in an acceptable compromise in accuracy and efficiency [9].

Consequently, the experimental paradigm has shifted from large-scale complex studies to multi-scale studies that validate material models at various length scales. Simulations that are physically based and less empirical can yield a higher level of prediction [9]. Furthermore, Eriten [10] described how a realistic and reliable SLM process simulation model should be simple and capture the physical aspects involved in the workflow. As a result of the significant enhancement in computational capabilities, discrete multi-scale

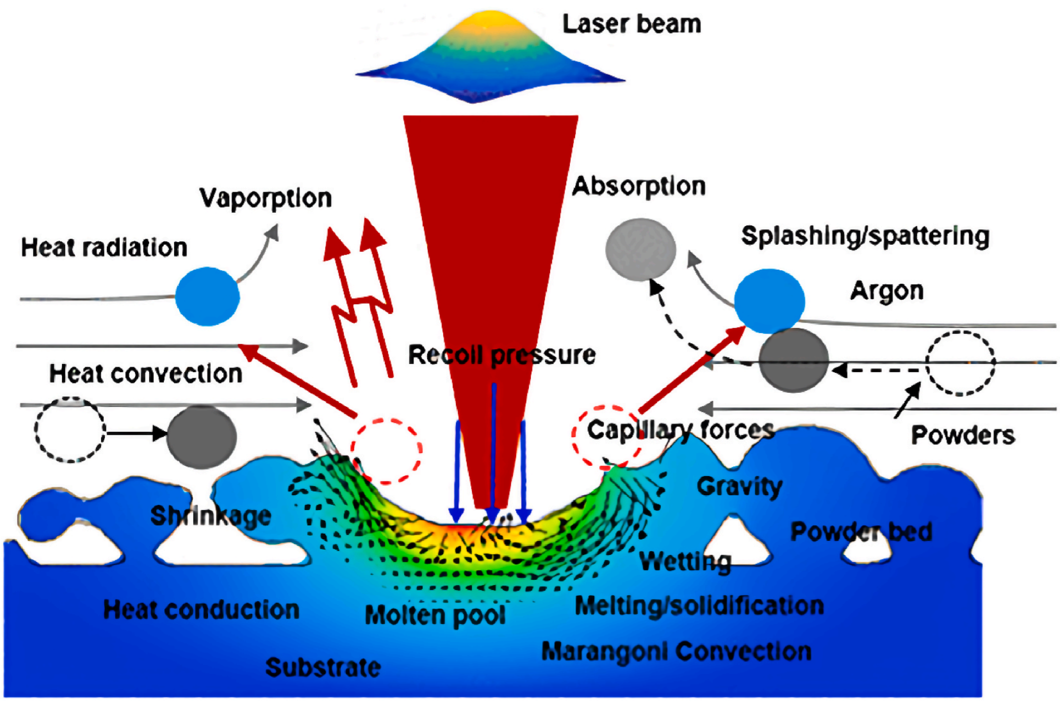


Fig. 1. Physics interaction in metal PBF technology [11].

models can meet the second criterion. Practicality, however, would be lacking. Multi-scale physics, on the other hand, would fit both criteria. However, physics is integrally interconnected, and sequential simulations cannot capture significant interactions - for example, modelling deformable bodies when aerodynamic forces are present and analysing conjugate heat transfer [10]. Thus, a Multiphysics approach is required for a modelling approach that effectively emulates and analyses physics interactions. Fig. 1 shows physics interactions in Metal Powder Bed Fusion Technology. Powder solidifies and shrinks when the beam melts it, which results in phase transformations and separations as part of the microstructure evolution. Absorption, heat transfer, radiation, wetting, convection, and release of capillary forces all co-occur.

2.2. Literature review and bibliometric analysis

A literature review and bibliometric analysis of Multi-scale Multiphysics SLM Simulation Environments are conducted in the preliminary section of this study. The first step involved identifying the information sources. Based on reviews of scientific databases, including Scopus, Web of Science, PubMed, IEEE Xplore, ScienceDirect, Directory of Open Access Journals (DOAJ), Journal Storage (JSTOR), Compendex, ASME library, ASTM, SPIE Digital library, Applied Science & Technology, Biological & Agriculture Index Plus, and Biological Sciences Database. These databases are the most comprehensive collection of scientific information and provide the largest database of multidisciplinary scientific literature. The following criteria were used to select articles for inclusion.

1) C1 - Article types must be research papers, proceedings papers, or reviews.
2) C2 – Articles must be written in English.
3) C3 – Articles must be no older than 20 years.

A general search was conducted in these databases using the search string Multi-scale Multiphysics, SLM, and Simulation Environment. Then, duplicates and articles not meeting the C1, C2, and C3 criteria were discarded. The collected articles were sorted by

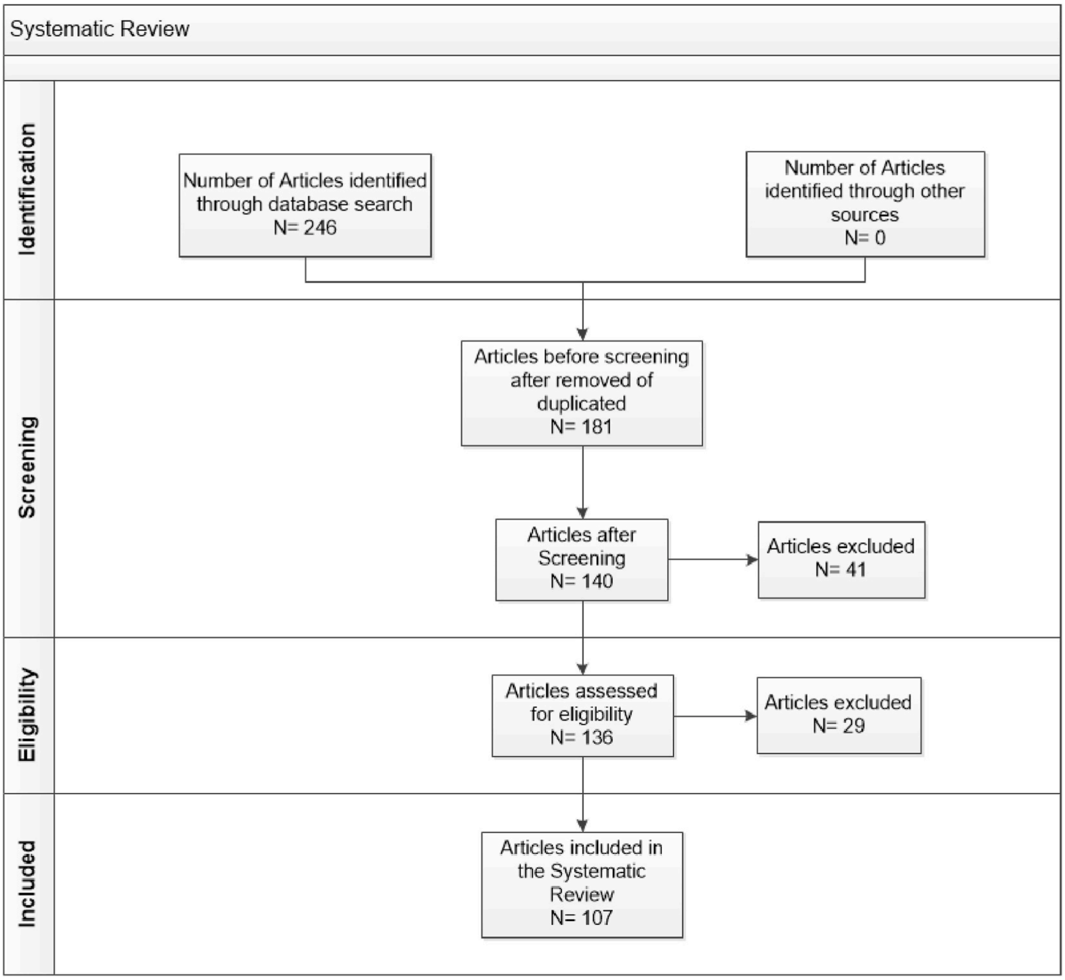


Fig. 2. Flow diagram for systematic bibliometric analysis.

titles, abstracts, and full text. A detailed flow chart of the information-gathering process is shown in Fig. 2.

2.3. Bibliometric data

It is imperative to note that this section does not provide an exhaustive listing of all the software available at the time of study (May 2020–October 2021). From the bibliometric analysis, it is evident that Ansys Additive Print, Flow-3D, Comsol Multiphysics, ESI Additive Manufacturing, Genoa 3DP, Amphyon, Simufact Additive, Autodesk Netfabb, and Simulia are currently the most widely used Multi-scale Multiphysics SLM Simulation Environments.

Based on the bibliometric listed in Table 1, Ansys Additive Print, Autodesk Netfabb, and Simufact Additive are the three most prevalent simulation environments for Multi-scale Multiphysics SLM. Furthermore, the most recent publications explore Simufact Additive, Amphyon, and Ansys Additive Print. It is evident from the 71 % increase in articles published over the last seven years that it is a topic of growing interest. Fig. 3 shows a breakdown of the number of publications related to Multi-scale Multiphysics SLM Simulation Environments by year. Additionally, it is worth noting that the initial studies on the topic were conducted in 2000. An estimate of the annual licence cost for each environment is shown in Fig. 4. It is important to note that Comsol offers a perpetual licence with an annual maintenance fee of 20 %. Over the long run, it is the least costly system. The purpose of exploring a large range of laser melting processes in the literature is to highlight the application of simulation modelling environments in replicating laser melting processes, which justifies their effectiveness for SLM while not deflecting from the focus of the study.

2.4. Review of multi-scale multiphysics SLM simulation environments

A growing body of literature shows that Multi-scale Multiphysics SLM Simulation Environments have primarily been used to investigate, evaluate, and improve SLM processes using Simulation Environment Capabilities, namely Modelling and Simulation, Design, Materials, Build Process, and Post-processing. In recent decades, Multi-scale Multiphysics SLM Simulation Environments and their Application Areas are presented chronologically in Table A1. The data presented is compiled in Fig. 5. This illustration shows that Ansys Additive Print (20 %), Simufact Additive (18 %), Autodesk Netfabb (18 %), and Simulia (14 %) have been the most popular Multi-scale Multiphysics SLM Simulation Environments over the years. This review is limited to simulation tools with a minimum usage ratio of 1 %, as per the available literature (see Fig. 6).

The literature review findings are summarised in Table A of the appendix. Table A presents the findings of 107 analysed publications related to Multi-scale Multiphysics SLM Simulation Environments. It also presents findings from studies examining the capabilities of prominent Multi-scale Multiphysics Environments in different applications, which are essential for a reliable SLM Simulation Environment. Table B presents a brief description of the mathematical methods of these tools.

3. Method

3.1. Overview

The study follows a twofold approach. The effectiveness of Multi-scale Multiphysics Simulation Environments is evaluated using literature-based SWOT-ANP analysis, which analyses the features of the review systems. In contrast, the experiment's design evaluates the system's reliability. It measures the system's ability to predict SLM outcomes with minimum deviation.

3.2. Effectiveness of multi-scale multiphysics simulation environments

3.2.1. SWOT analysis

This analysis identifies the strengths and weaknesses of the SLM Simulation Environments and identifies and analyses opportunities and threats. A SWOT analysis is critical in deciding if a particular SLM Simulation Environment suits a particular application. Analysing the Simulation Environment Strengths identifies the features and functionalities required for reliable, realistic simulation modelling. Weaknesses provide useful information about areas of the environment that require improvement. Finally, opportunities

Table 1
Matrix of Multi-scale Multiphysics SLM Simulation Environments and the number of articles published annually over the past two decades.

MULTI-SCALE MULTIPHYSICS SLM NUMBER OF PUBLISHED ARTICLES (2000 – 2021) SIMULATION TOOLS 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22

Ansys Additive Print						2	2	2	4	2	3	1		1	1	3	5	1	1
Flow-3D						1						1	1	1		1	2		
Comsol Multiphysics®									1	1		2	1	1		3	1	5	
ESI AM																	1		
Genoa 3DP				1									2	1		1	1	1	
Amphyon								1		1	1		1	1		1	4	3	
Simufact Additive							2				2			2	6	5	6	4	
Netfabb	1		1				1		3	3	2	5	1	1	1	3	2	4	
Simulia		1		1	1				1	1		3	2	1		6	3	2	

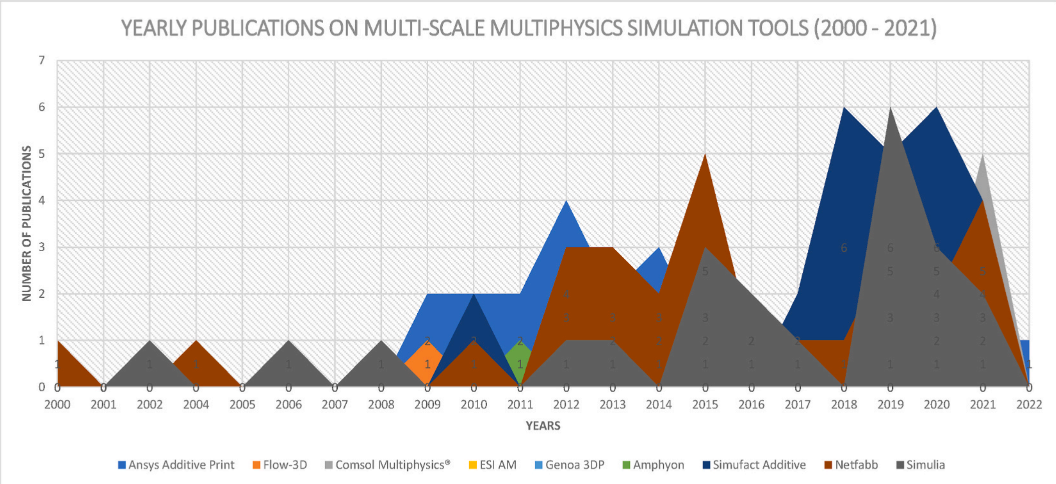


Fig. 3. Year-by-year breakdown of literature production on multi-scale multiphysics simulation tools.

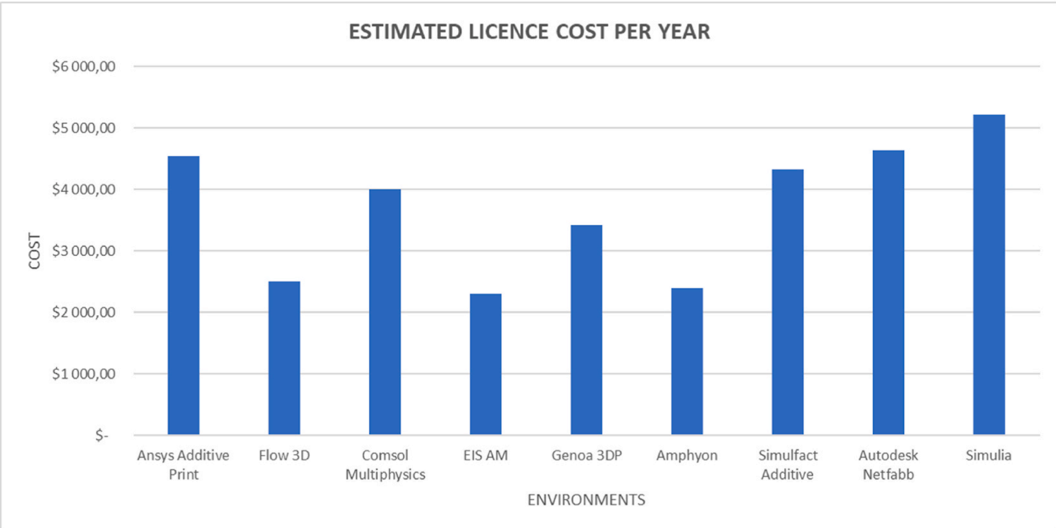


Fig. 4. Estimated licence cost of multi-scale multiphysics simulation tools.

and threats provide valuable insight into specific features that may encourage or hinder the adoption of simulation tools [12].

3.2.2. Analytic Network Process (ANP)

The ANP is essentially a method for analysing intangible factors through pairwise comparisons based on judgements indicating the relative dominance of one element over another concerning a particular property [13]. It is described as a decision-making method and a generalisation of the classic Analytic Hierarchy Process (AHP). With an ANP, complex decision problems (including non-hierarchical ones) can be modelled. This method allows items and systems to be selected based on the performance of independent factors [14].

Most decision problems cannot be structured hierarchically because they involve interaction and dependence between elements at different levels in a hierarchy [15]. In contrast to the AHP, a framework with a unidirectional hierarchical relationship between levels, the ANP allows for complex relationships between levels and attributes [16].

3.2.3. Reliability of multi-scale multiphysics simulation environments

Design of Experiment - The level of thermal distortion incurred in SLMed parts from physical and simulated environments is compared using a one-factor at a time (OFAT) DoE to validate the reliability of Multi-scale Multiphysics Simulation Environments. Distortion is a recurring problem in SLM processes.

In additive manufacturing, distortion is a deviation from a part's intended geometry [17]. Due to the high temperatures in the SLM process, parts are subjected to thermal stresses, causing distortions [18]. Mukalay et al. [7] stated that laser power is the major cause of

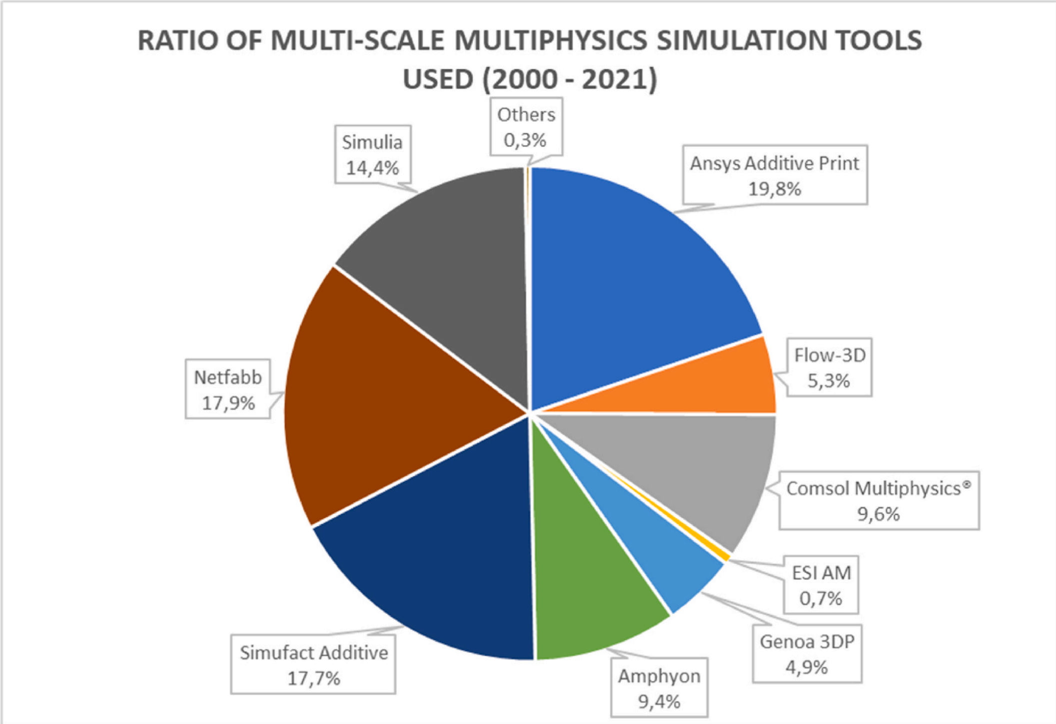


Fig. 5. Utilisation of multi-scale multiphysics SLM simulation environments through existing literature.

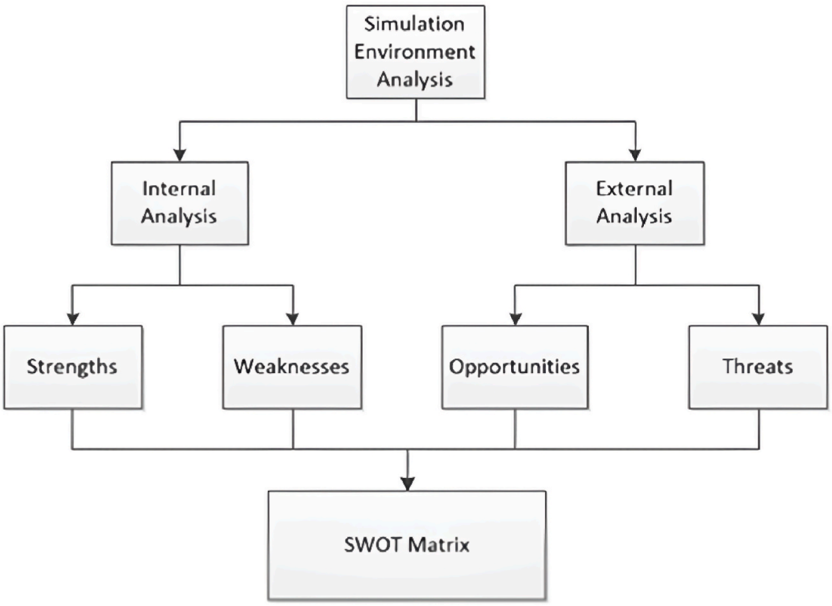


Fig. 6. Applied SWOT analysis framework – modified from Gorener (2012).

thermal-induced distortion in SLMed parts. As part of this experiment, laser power will be varied while other manufacturing parameters will remain constant.

3.2.4. SWOT-ANP methodology

3.2.4.1. Overview. In this approach, ANP models are used in conjunction with SWOT analyses. When using ANP within a SWOT framework, the objective is to qualify SWOT factors systematically and equate their intensity levels [19]. Researchers have utilised this framework in numerous studies to overcome the lack of a systematic mechanism to quantify the performance of the assessed factors in SWOT analysis [8]. In addition to assessing the level of accomplishment of pre-defined capabilities, ANP is used to assess the priority ranking of pre-defined capabilities [13].

3.2.4.2. ANP model. Fig. 7 illustrates the four levels of the ANP model. Since the third-level capabilities are independent, it is a non-hierarchical model. As a result of the application of the ANP model, each capability is assigned a priority rate.

3.2.4.3. Key system capabilities. An initial step in developing a SWOT analysis of SLM Simulation Environments is to analyse the performance of pre-defined capabilities for each Simulation Environment. These are Modelling, Simulation, Design, Material, Build Process, and Post-processing. These capabilities are essential for a realistic and reliable SLM Simulation Environment [20]. The following sections provide an overview of each capability.

a. Modelling and Simulation: Simulations and modelling are conducted at various stages in the SLM value chain. For example, process simulations are used to simulate the real SLM process, to help with part selection and parameter selection, or to analyse how variations in parameter settings affect the behaviour of the part. Models can be generated layer by layer through Multiphysics modelling, from the microstructure to the final assembly. Among its benefits is the ability to analyse the effects of manufacturing processes (such as distortion, residual stress, etc.), leading to more accurate estimations of part quality and product lifecycle models. Moreover, models can also have a significant impact on the production process. As a result, a design is iterated until its mechanical or thermal performance is fully optimized [21].
b. Design: Design capability is the ability to create or modify designs. New digital parts can be created with CAD programmes or by scanning existing parts in three dimensions. During the design phase, design considerations should include slicing and design software, interoperability among distinct SLM steps, and traceability from the physical structure to scan data to the CAD model. Furthermore, finite element analysis (FEA) and computational fluid dynamics (CFD) can also be used to optimize the topology, shape, and topography of parts through static and dynamic analysis. A system's design capability may better understand parts' structural, material, thermal, and flow properties and factors such as bending stiffness to weight [22].
c. Materials: The value chain of SLM is heavily reliant on materials. This capability involves software tools and material databases that identify relationships between material properties and SLM build parameters [23].
d. Build Process: During the Build Process, STL files are repaired, automated support structures are generated, orientation is selected, nesting algorithms are applied, collision detection is performed, job files are created, job files are loaded directly from printers, and updates are made to the logs. This capability improves built-in support structures' number, position, and size. Post-processing costs will rise by including more support structures, thus lowering the surface quality. The support structures eliminate curling, reduce the risk of the re-coater dislodging the structure, conduct heat (process stability), and stop molten metal from sinking through the

Fig. 7. Anp model for SWOT performance evaluation.

powder bed for down-facing areas and preventing dross formation. An essential part of the building process is improving the locating, numbering, and locating supports. The building process monitoring involves monitoring temperature, distortion, material levels, feedback loops of the construction process, and regulating process parameters as the work progresses [24].

e. Post-Processing: Post-processing, the final step in the SLM value chain, involves removing support structures, smoothing the part, and painting it. During post-processing, the end product's quality is usually enhanced, and the design specifications are met. Post-processing improves parts in terms of surface characteristics, geometric accuracy, aesthetics, and mechanical properties. Drilling, milling, and polishing are all available options. Heat treatment and shot peening are usually used to increase the surface's tactile and mechanical properties. As part of the hot isostatic pressing process, parts are heated and pressed at high pressure for a set period in an inert atmosphere. When materials are heated to a high temperature, voids collapse, and then the surface of the voids is fused, removing defects from the materials, and improving their mechanical properties, including fatigue resistance. Electric polishing is generally used to smooth, deburr, brighten, and passivate surfaces, especially those exposed to abrasive media [25].

3.2.4.4. Performance Evaluation. The performance assessment is conducted by assigning a degree of performance or achievement of the pre-defined capabilities based on the scale developed by Cheng et al. [26] - 0 (very low achievement), 0.25 (low achievement), 0.5 (fair achievement), 0,75 (high achievement), and 1 (very high achievement). In addition, the priority rate of each capability is another key parameter in the ANP model. Fig. 8 provides these values. Performance Indices of Multi-scale Multiphysics SLM Simulation Environments are calculated based on the capabilities' priority rate and degree of achievement [8]. Fig. 8 illustrates that Modelling and Simulation (45 %) have been the most assessed capabilities of Multi-scale Multiphysics SLM Simulation tools, followed by Design (24 %).

The Performance Index is calculated as follows:

$$Local\ Performance\ Index = w_i x_i \quad (1)$$

$$Global\ Performance\ Index = \sum_i w_i x_i \quad (2)$$

Where;

w_i: Priority Rate;

x_i: Degree of Achievement.

Steps of the Methodology.

Step 1. SWOT analysis – Identifying the strengths, weaknesses, opportunities, and threats based on the pre-defined capabilities.

Step 2. Degree of Achievement – Determination of the degrees of achievement of the SWOT factors with a 0–1 scale.

Step 3. Priority – Determination of the priority of each capability concerning the literature review and biometric analysis – See Fig. 7.

Step 4. Local Performance Index – Determination of the Performance Index of each capability – (1).

Step 5. Global Performance Index – Determination of the Performance Index of each Multi-scale Multiphysics SLM Simulation

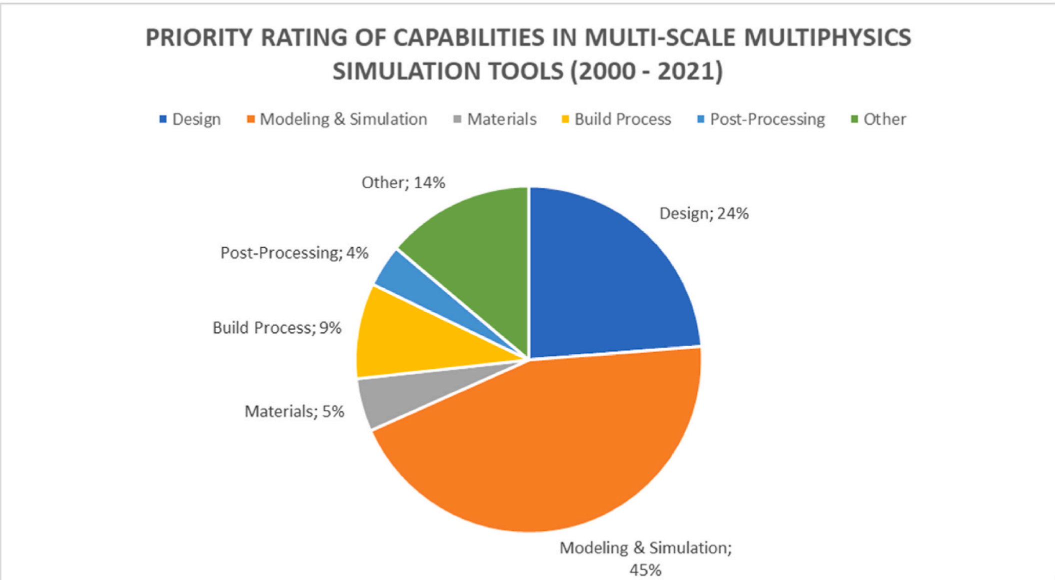


Fig. 8. Priority rating of investigated system capabilities through the existing literature.

Environment – (2).

3.2.5. *Experimental validation*

3.2.5.1. Analytical modelling. The simulation model developed in this study follows the analytical model presented in Fig. 9. Process and material parameters serve as inputs, the three-dimensional distortion values in the *x, y*, and *z* directions are outputs, and the temperature profile, thermal stresses, and residual stress are computed as intermediate variables. The model followed in this study consists of analytical thermal, thermal stress, residual stress models, and distortion models.

a. Thermal Model:

The temperature profile is determined through an analytical thermal model considering the heat input from the moving laser and

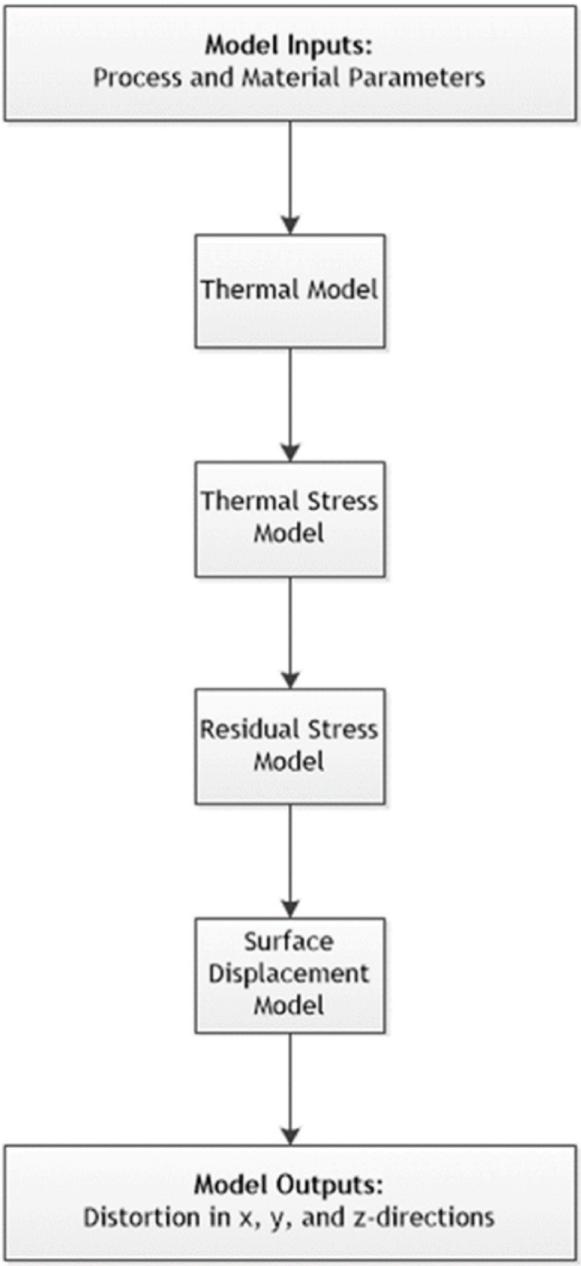


Fig. 9. Analytical modelling flowchart of part distortion in Ti6Al4V-SLM processes [27].

Table 2
Experiment Process parameters.

PROCESS PARAMETERS	UNIT	PART 1 PART 2	PART 3	PART 4	PART 5
Laser Power	W	200 160	130	80	40
Laser Scanning Speed	mm/s	750 750	750	750	750
Laser Spot Diameter	μm	70 70	70	70	70
Hatch Distance	mm	0.08 0.08	0.08	0.08	0.08
Heat Transfer Coefficient	W/(m^2.K)	20 20	20	20	20
Dynamic Velocity	Pa.s	0.002 0.002	0.002	0.002	0.002
Melting Latent heat	J.Kg^{-1}	419000 419000	419000	419000	419000
Layer Thickness	μm	30 30	30	30	30
Initial Baseplate Temperature	°C	200 200	200	200	200
Specimen Dimensions	mm	35 × 15 x 2 (L x W x H)			

heat loss from the boundary heat loss due to convection and radiation. The part boundary at the uppermost layer is mathematically discretised into many sections (heat sinks) due to the non-uniform temperature distribution, which leads to non-uniform heat losses. σ_x and σ_z, are the normal stress and T_{xz} and T_{zx} is the shear stress at the cross-sectional area on the x-z plane [27]. The moving point heat source solution equation is given by Eq. (3):

$$\theta_L(x,y,z) = \frac{P_\eta}{4\pi kR(T_m - T_0)} \exp\left(\frac{-V(R+x)}{2K}\right) \tag{3}$$

where P is the laser power, η is the absorption, V is the scan velocity, K is the thermal diffusivity (K = k/ρc, where k, ρ, c are the thermal conductivity, density, and specific heat, respectively), $R^2 = x^2 + y^2 + z^2$ is the total distance from the laser source, $x = X - X_L$, $y = Y - Y_L Y_L$, $z = Z - Z_L$ are the corresponding distances from the laser source, $\theta = (T - T_0)/(T_m - T_0)$ is the dimensionless temperature, and T_0 and T_m are the room and material melting temperatures, respectively [27].

The heat sink solution is derived from the heat source solution with zero moving velocity and equivalent power for heat loss from convection and radiation. It is expressed as follows in Eq. (4):

$$\theta_B(x,y,z) = \frac{1}{4\pi kR(T_m - T_0)} \times \sum_{i=0}^{n} A_i\left[h(T_i - T_0) + \varepsilon\sigma\left(T_i^4 - T_0^4\right)\right] \tag{4}$$

Where A_i is the area of the heat sink, T_i is the temperature of the heat sink that is estimated by the moving point heat source solution, h is the convection coefficient, ε is the emissivity, and σ is the Stefan-Boltzmann constant [27].

The final temperature solution is constructed from the superposition of the moving point heat source solution and heat sink solution. It is given by Eq. (5):

$$\theta(x,y,z) = \theta_L(x,y,z) - \theta_B(x,y,z) \tag{5}$$

b. Thermal Stress Model:

The high-density laser power leads to inconsistent temperature distribution, creating thermal stress. The thermal stress is determined based on the thermos-elasticity theory [28]. They are expressed as follows in Eqs. 6–10:

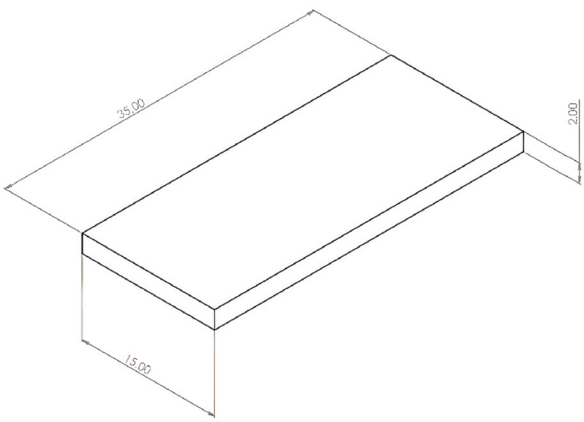


Fig. 10. Specimen drawing (mm).

Table 3
SWOT analysis matrix of multi-scale multiphysics SLM simulation environments.

SIMULATION TOOLS	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
AMPHYON	**Material** – Comprehensive material database	**Modelling & Simulation** – Limited capabilities **Design** – Limited FEA capabilities **Build Process** – Model/ Physics based **Post-Processing** – Limited capability (suitable for Pre-processing).	AMPHYON provides a Multi-scale Multiphysics Simulation Environment for AM Process Modelling. AMPHYON's Multi-scale Multiphysics capabilities can predict porosity, residual stress, distortion, thermal behaviour, and mechanical properties. AMPHYON provides direct equipment selection capabilities.	Limited capabilities in Modelling and Simulation, Design, Build Process, and Post-processing.
ANSYS ADDITIVE PRINT	**Build Process** – End to End process	**Modelling & Simulation** – Limited capabilities **Design** – Limited design capabilities **Material** - The material library is limited to explicit materials. **Post-Processing** – Limited post-processing capabilities	ANSYS offers advanced capabilities in Design Analysis, Output Prediction, Multi-scale Multiphysics, and Simulation Modelling. ANSYS's Multi-scale Multiphysics capabilities can predict porosity, distortion, residual stress, thermal behaviour, and mechanical properties.	Limited capabilities in Modelling and Simulation, Design Complexity, Material availability, Library resources, and Post-processing. ANSYS does not provide equipment selection capabilities.
COMSOL Multiphysics	**Build Process** – End to End **Post-Processing** – Robust capabilities	**Modelling & Simulation** - Highly complex **Design** - Limited FEA and CFD capabilities **Material** - No Industry Specific Database	COMSOL offers a flexible environment for Multi-scale Multiphysics Simulation Modelling via its features such as Continuous Modelling, Motion Modelling, Stochastic Modelling, Design Analysis, Mesh Generation, and Post-processing. COMSOL's Multi-scale Multiphysics capabilities can predict porosity, residual stress, distortion, mechanical properties, and thermal behaviour.	A major limitation of COMSOL is its high level of system complexity, limited FEA capability, and low mesh convergence rate. Tools like MATLAB need to be integrated better. Numerical modelling is also limited in the system. COMSOL does not provide equipment selection capabilities.
ESI AM	-	**Modelling & Simulation** – Limited capabilities **Design** - Limited design analysis capabilities (CFD & FEA) **Material** – Limited library **Build Process** – Model/ Physics based **Post-processing** - Limited capabilities	ESI Additive Manufacturing provides a comprehensive simulation modelling solution for Metal Additive Manufacturing. ESI provides users with access to experimental data. ESI AM's Multiscale Multi-physics capabilities can predict porosity, residual stress, distortion, thermal behaviour, and mechanical properties.	ESI has limitations regarding analysis challenges (CFD and FEA) and building process capabilities—limited models and physics. ESI does not provide equipment selection capabilities.
FLOW-3D	**Modelling & Simulation** – Robust capabilities	**Design** – No FEA capabilities **Material** – Limited library **Build Process** – Model/ Physics based **Post-processing** – Limited capabilities	FLOW-3D offers simulation solutions for binder jetting, PBF, and DED. FLOW-3D's Multiscale Multi-physics capabilities can predict porosity, distortion, and mechanical properties.	Using a third-party tool for Design Analysis is required as FLOW-3D AM does not offer FEA capabilities. FLOW 3D does not provide equipment selection capabilities.
GENOA 3DP	**Modelling & Simulation** – Robust capabilities **Build Process** – End to End	**Design** – Limited FEA capabilities **Material** – Limited library **Post-processing** – Limited capabilities	With its advanced Multi-scale Progressive Failure Modelling and analysis approach, ability to support external mesh from FEA software, and ability to simulate environmental effects, GENOA 3DP is an effective simulation model for AM processes. GENOA's Multiscale Multi-physics capabilities can predict can porosity, residual stress, distortion, thermal behaviour, and mechanical properties. GENOA provides direct equipment selection capabilities.	GENOA 3DP offers limited FEA capabilities (third-party tools must be used) and limited Material databases and post-processing functions.

(*continued on next page*)

Table 3 (*continued*)

SIMULATION TOOLS	STRENGTHS	WEAKNESSES	OPPORTUNITIES	THREATS
NETFABB Autodesk	**-**	**Modelling & Simulation** – Limited capabilities **Design** – Limited FEA capabilities **Material** – Limited library **Build Process** – Model/ Physics based **Post-processing** – Limited capabilities	NETFABB enables the direct import of many different CAD files (no conversion errors). An all-in-one solution that includes design enhancement, manufacturing preparation, and building simulation tools. NETFABB's Multi-scale Multiphysics can predict porosity, distortion, and mechanical properties.	No metal heat treatment simulation can be done due to limited FEA capabilities - other tools such as Autodesk Nastran In-CAD have to be used, inefficient workflows, and system failures. NETFABB does not provide equipment selection capabilities.
SIMUFACT Additive	**Build Process** – End to End process **Post-processing** – Robust capabilities	**Modelling & Simulation** – Limited Finite Element Modelling (FEM) capabilities **Design** - Limited FEA capabilities **Material** – Limited library	The GUI's versatility, the AM process's simulation into the post-processing stage, and the ability to predict output. SIMUFACT can predict porosity, distortion, residual stress, thermal behaviour, and mechanical properties through a combination of process-based simulation and material models. Furthermore, it offers access to experiment data by partnering with leading organisations in additive manufacturing. SIMUFACT provides direct equipment selection capabilities.	Materials' anisotropic properties cannot be considered or interfered with, and finite element modelling is limited.
SIMULIA	_	**Modelling & Simulation** - Limited FEM capabilities **Design** – Limited FEA capabilities **Material** – Limited library **Build Process** – Model/ Physics based **Post-processing** – Limited capabilities	SIMULIA enables the configuration, instantiating, and running of Simulation templates. The Eigenstrain method is used to simplify complex geometries, as are new voxel-based meshes. SolidWorks compatible. Static tests can be conducted using SIMULIA. The mesh quality display provided by SIMULIA is satisfactory. The Dassault Systèmes digital platform enables collaboration with the world's leading digital manufacturers. SIMULIA's Multi-scale Multiphysics capabilities can predict porosity, residual stress, distortion, thermal behaviour, and mechanical properties.	There is no volume analysis of negative space, limited Finite Element modelling capability, and limited options for mesh element types. SIMULIA does not provide equipment selection capabilities.

$$\sigma_{xx}^{therm}(x,z) = -\frac{\alpha E}{1-2v}\int_0^{\infty}\int_{-\infty}^{\infty}\left(G_{xh}\frac{\partial T}{\partial x}(x',z') + G_{xv}\frac{\partial T}{\partial z}(x',z')\right)dx'dz' + \frac{2z}{\pi}\int_{-\infty}^{\infty}\frac{p(t)(t-x)^2}{\left((t-x)^2+z^2\right)}dt - \frac{\alpha ET(x,z)}{1-2v} \tag{6}$$

$$\sigma_{zz}^{therm}(x,z) = -\frac{\alpha E}{1-2v}\int_0^{\infty}\int_{-\infty}^{\infty}\left(G_{zh}\frac{\partial T}{\partial x}(x',z') + G_{zv}\frac{\partial T}{\partial z}(x',z')\right)dx'dz' + \frac{2z}{\pi}\int_{-\infty}^{\infty}\frac{p(t)(t-x)^2}{\left((t-x)^2+z^2\right)}dt - \frac{\alpha ET(x,z)}{1-2v} \tag{7}$$

$$\sigma_{xz}^{therm}(x,z) = -\frac{\alpha E}{1-2v}\int_0^{\infty}\int_{-\infty}^{\infty}\left(G_{xzh}\frac{\partial T}{\partial x}(x',z') + G_{xzv}\frac{\partial T}{\partial z}(x',z')\right)dx'dz' + \frac{2z}{\pi}\int_{-\infty}^{\infty}\frac{p(t)(t-x)^2}{\left((t-x)^2+z^2\right)}dt - \frac{\alpha ET(x,z)}{1-2v} \tag{8}$$

$$\sigma_{yy}^{therm}(x,z) = \left(\sigma_{xx}^{therm} + \sigma_{zz}^{therm}\right) - \alpha ET(x,z) \tag{9}$$

$$p(t) = \frac{\alpha ET(x, z=0)}{1-2v} \tag{10}$$

where the thermal stresses σ_{xx}^{therm}, σ_{yy}^{therm}, σ_{zz}^{therm}, σ_{xz}^{therm} are following Green's functions (G_{xh}, G_{zh}, G_{xzh}, G_{xv}, Gzv, G_{xzv}) under plane strain conditions and provide an analytical solution to calculate the thermal stress [29]. α, E and v are the thermal expansion coefficient, elastic modulus, and Poisson's ratio.

c. Residual Stress Model

The residual stress results from the contraction and extension of the material throughout the heating and cooling phases. Elastoplastic relaxation procedures determine the residual stress [30]. The plane strain assumption is considered. A hybrid function links the elastic and elastoplastic solutions. The residual stress equation is given by Eq. 11–13:

$$\psi = 1 - \exp\left(-K\frac{3h}{2G}\right) \tag{11}$$

$$\varepsilon_{xx} = \psi\varepsilon_{xx} \tag{12}$$

$$\varepsilon_{yy} = 0 \tag{13}$$

where ε_{xx}; ε_{yy} are elastic solutions, ε_{xx} is an elastoplastic solution, Ψ is the hybrid function with κ, h, G is denoted model constant, elastic modulus, and shear modulus $\left(G = \frac{E}{2(1+v)}\right)$.

Those equations are expressed as follows in Eq. 14–16:

$$\varepsilon_{xx} = \frac{1}{E}\left[\sigma_{xx} - v\left(\sigma_{yy} + \sigma_{zz}\right)\right] + \frac{1}{h}\left(\sigma_{xx}n_{xx} + \sigma_{yy}n_{yy} + \sigma_{zz}n_{zz} + 2T_{xz}n_{xz}\right)n_{xx} \tag{14}$$

$$\varepsilon_{yy} = \frac{1}{E}\left[\sigma_{yy} - v(\sigma_{xx} + \sigma_{zz})\right] + \frac{1}{h}\left(\sigma_{xx}n_{xx} + \sigma_{yy}n_{yy} + \sigma_{zz}n_{zz} + 2T_{xz}n_{xz}\right)n_{xx} \tag{15}$$

The relaxation procedure is employed to determine the residual stress as the non-zero components, $\sigma_{zz} = \sigma_{zz}^R, T_{xz} = T_{xz}^R,$.

$$\Delta\sigma_{zz} = -\frac{\sigma_{zz}^R}{M}, \Delta T_{xz} = -\frac{T_{xz}^R}{M}, \Delta\varepsilon_{zz} = -\frac{\varepsilon_{zz}^R}{M} \tag{16}$$

d. Distortion Model

The part thickness is considered infinitesimal, so it can be assumed to be a surface. The residual stress-induced distortion is determined from the computed residual stress and residual strain in the surface and subsurface through the surface displacement model [27]. The distortion of geometric deviation of the part distortion is expressed as follows in Eq. 17–21:

$$w = 2\mu\sum_{n=1}^{N}\int\Omega\varepsilon_{ij,n}^{P}(A)d\Omega = \sum_{n=1}^{N}\varepsilon_{ij,n}^{P}(M)K_{ij} \tag{17}$$

Where w is the surface displacement, $\varepsilon_{ij,n}^{P}$ is the residual strain, K_{ij} is an operation function, and D is an operation factor.

$$K_{ij} = \begin{bmatrix} D_{ij}(a_1 + \Delta x_1, a_2 + & \Delta x_2, a_3 + & x_3) - \\ D_{ij}(a_1 + \Delta x_1, a_2 + & \Delta x_2, a_3 - & \Delta x_3) - \\ D_{ij}(a_1 + \Delta x_1, a_2 - & \Delta x_2, a_3 + & \Delta x_3) + \\ D_{ij}(a_1 + \Delta x_1, a_2 - & \Delta x_2, a_3 - & \Delta x_3) - \\ D_{ij}(a_1 - \Delta x_1, a_2 + & \Delta x_2, a_3 + & \Delta x_3) + \\ D_{ij}(a_1 - \Delta x_1, a_2 + & \Delta x_2, a_3 + & \Delta x_3) + \\ D_{ij}(a_1 - \Delta x_1, a_2 - & \Delta x_2, a_3 + & \Delta x_3) - \\ D_{ij}(a_1 - \Delta x_1, a_2 - & \Delta x_2, a_3 + & \Delta x_3) - \end{bmatrix} \tag{18}$$

$$D = \frac{1}{\pi} \begin{bmatrix} (-vx\ln(y+R) - (1-2v) & \times & z\,tan^{-1}\left(\frac{y+z+R}{x}\right)) \\ (-vx\ln(y+R) - (1-2v) & \times & (-vx\ln(y+R) - (1-2v)) \\ 2(1-v)\left(\frac{y+z+R}{z}\right) + x\ln(y+R) & + & y\ln(x=R) - \frac{z}{2}\theta) \\ (2vR-(1-2v)\times & \times & z\ln z(z+R)) \\ \left(2x tan^{-1}\left(\frac{y+z+R}{x}\right)\right. & + & y\ln(z+R)) \\ 2y\,tan^{-1}\left(\frac{y+z+R}{y}\right) & + & x\ln(z+R)) \end{bmatrix} \tag{19}$$

Where θ and R are the constants of the model expressed as follows:

$$\theta = -2\,tan^{-1}\left(\frac{xy}{zR}\right) \tag{20}$$

$$R = \sqrt{x^2 + y^2 + z^2} \tag{21}$$

3.2.5.2. Simulation modelling approach. The simulation modelling follows a two-step approach.

a. Simulation Model Development

The simulation model in this study was constructed using the analytical model outlined in the preceding section, and it was conducted across all the simulation tools assessed.

b. Results Analysis

The geometric deviation or distortion of the Ti6Al4V-SLMed part was assessed through non-linear FEA (See Table C in Appendix). The domain integration is given by Eq. (22):

$$a(u, \overline{u}) = \iint_{\Omega} \varepsilon(\overline{u}) : \sigma(u) d\Omega \tag{22}$$

3.2.5.3. Experimentation. The Thin Flat Plate approach is used in this study. SLMed thin flat plates with a maximum thickness of 2 mm are used for this approach. In this setting, distortion is measured by the degree to which the plate wraps after exposure to SLM parameters after being separated from the substrate.

With this approach, the level of distortion on the outside surfaces of the part could be predicted with very high accuracy. This approach is widely used to measure the level of distortion in SLM, and it is less expensive to use when compared with alternative methods such as trial and error with a real part and is less consequential when compared to the cantilever approach since all axes are equally affected under exposure to SLM parameters [31].

a. Equipment: A SLM 125 from SLM Solution was used for this experiment. During the simulation phase, Amphyon, Genoa 3DP, and Simufact allowed direct selection of the equipment from their databases, while Ansys, Comsol, Flow-3D, Netfabb, and Simulia required replicating equipment parameters manually.

Table 4
Performance index matrix of multi-scale multiphysics SLM simulation environments.

MULTI-SCALE MULTIPHYSICS SLM SIMULATION TOOL	CAPABILITIES	PRIORITY RATE	DEGREE OF ACHIEVEMENT	LOCAL PERFORMANCE INDEX
AMPHYON	Modelling & Simulation	0.24	0.75	0.178
	Design	0.45	0.25	0.113
	Materials	0.05	0.75	0.034
	Build Process	0.09	0.25	0.022
	Post-Processing	0.04	0.25	0.009
	Global Performance Index			0.356
ANSYS ADDITIVE PRINT	Modelling & Simulation	0.24	0.75	0.178
	Design	0.45	0.50	0.225
	Materials	0.05	0.25	0.011
	Build Process	0.09	1.00	0.086
	Post-Processing	0.04	0.50	0.018
	Global Performance Index			0.519
Comsol Multiphysics	Modelling & Simulation	0.24	0.75	0.178
	Design	0.45	0.25	0.113
	Materials	0.05	0.25	0.011
	Build Process	0.09	1.00	0.086
	Post-Processing	0.04	0.75	0.028
	Global Performance Index			0.416
ESI Additive Manufacturing	Modelling & Simulation	0.24	0.75	0.178
	Design	0.45	0.25	0.113
	Materials	0.05	0.25	0.011
	Build Process	0.09	0.25	0.022
	Post-Processing	0.04	0.50	0.018
	Global Performance Index			0.342
FLOW-3D	Modelling & Simulation	0.24	0.75	0.178
	Design	0.45	0.25	0.113
	Materials	0.05	0.5	0.023
	Build Process	0.09	0.25	0.022
	Post-Processing	0.04	0.50	0.018
	Global Performance Index			0,353
GENOA-3DP	Modelling & Simulation	0.24	0.75	0.178
	Design	0.45	0.25	0.113
	Materials	0.05	0.50	0.023
	Build Process	0.09	1.00	0.086
	Post-Processing	0.04	0.5	0.018
	Global Performance Index			0.418
NETFABB Autodesk	Modelling & Simulation	0.24	0.75	0.178
	Design	0.45	0.50	0.225
	Materials	0.05	0.50	0.023
	Build Process	0.09	0.25	0.022
	Post-Processing	0.04	0.50	0.018
	Global Performance Index			0.466
SIMUFACT Additive	Modelling & Simulation	0.24	0.75	0.178
	Design	0.45	0.25	0.113
	Materials	0.05	0.5	0.023
	Build Process	0.09	1.00	0.086
	Post-Processing	0.04	0.50	0.018
	Global Performance Index			0.418
SIMULIA	Modelling & Simulation	0.24	0.75	0.178
	Design	0.45	0.50	0.225
	Materials	0.05	0.50	0.023
	Build Process	0.09	0.25	0.022
	Post-Processing	0.04	0.50	0.018
	Global Performance Index			0.466

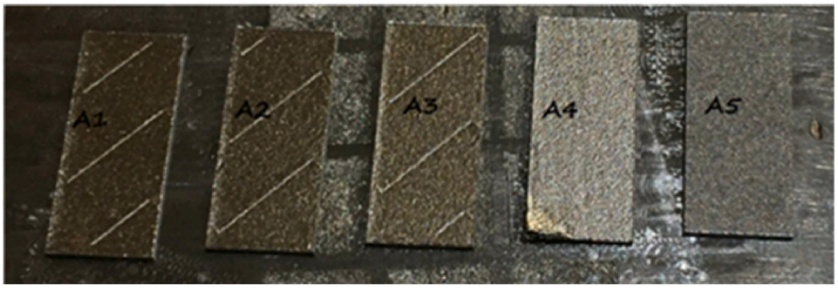


Fig. 11. Ti6Al4V -thin flat plate specimens.

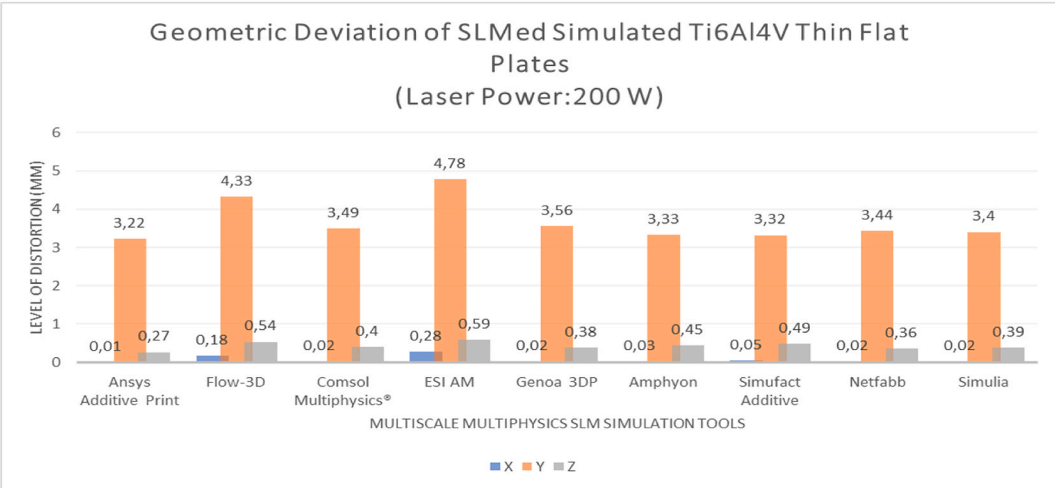


Fig. 12. Geometric deviation of SLMed simulated Ti6Al4V-thin flat plates (laser power: 200W) – A1.

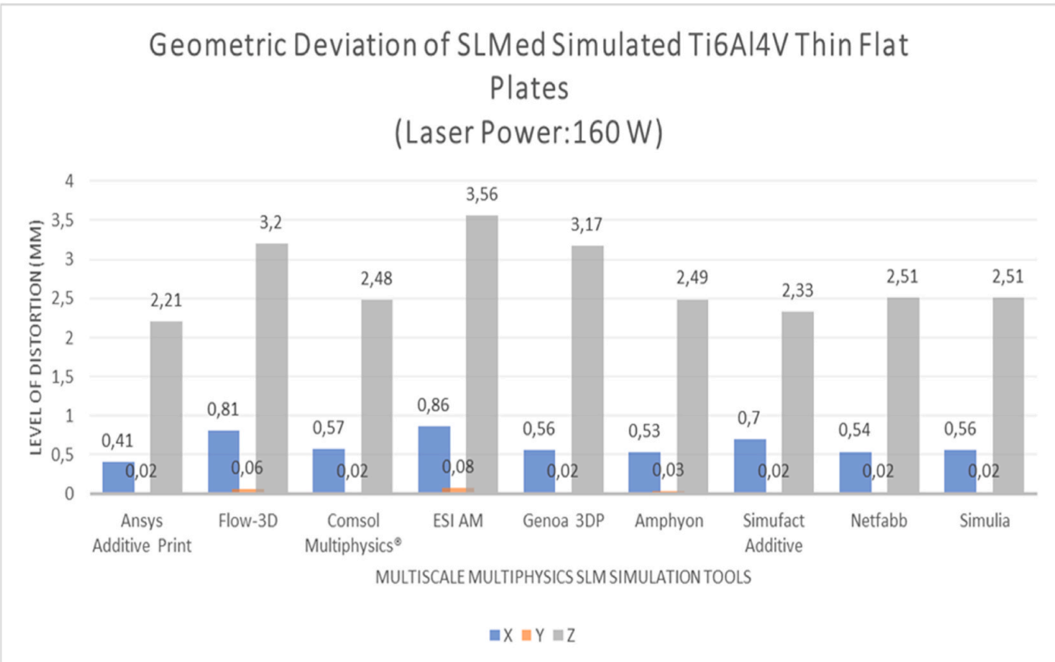


Fig. 13. Geometric deviation of SLMed simulated Ti6Al4V-thin flat plates (laser power: 160W) – A2.

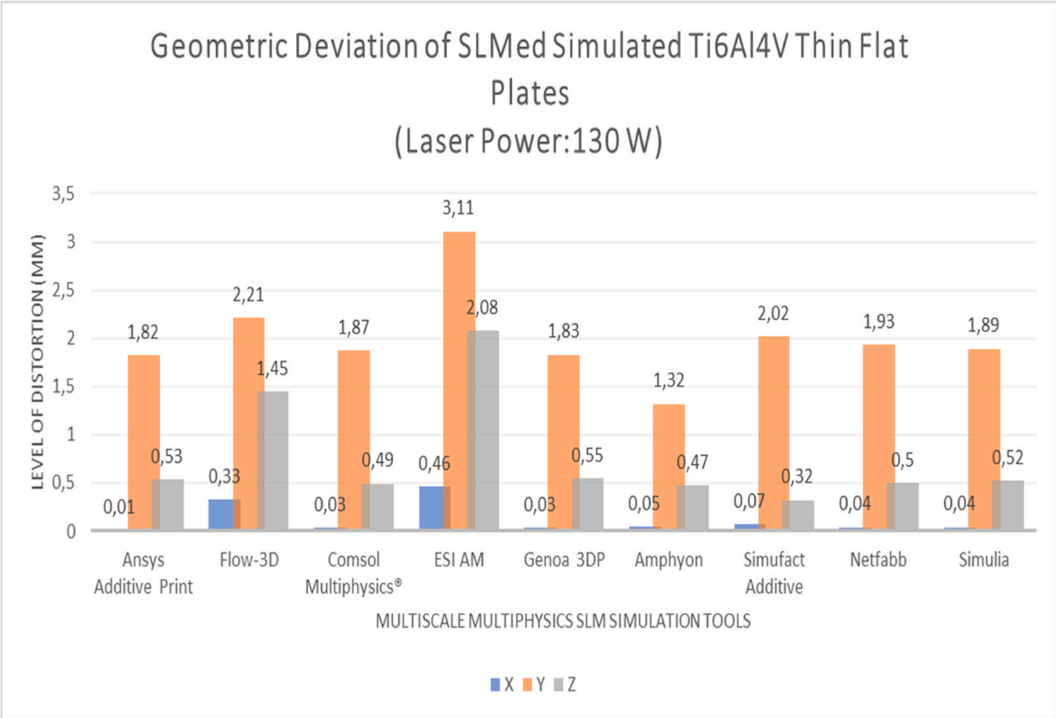


Fig. 14. Geometric deviation of SLMed simulated Ti6Al4V-thin flat plates (laser power: 130W) – A3.

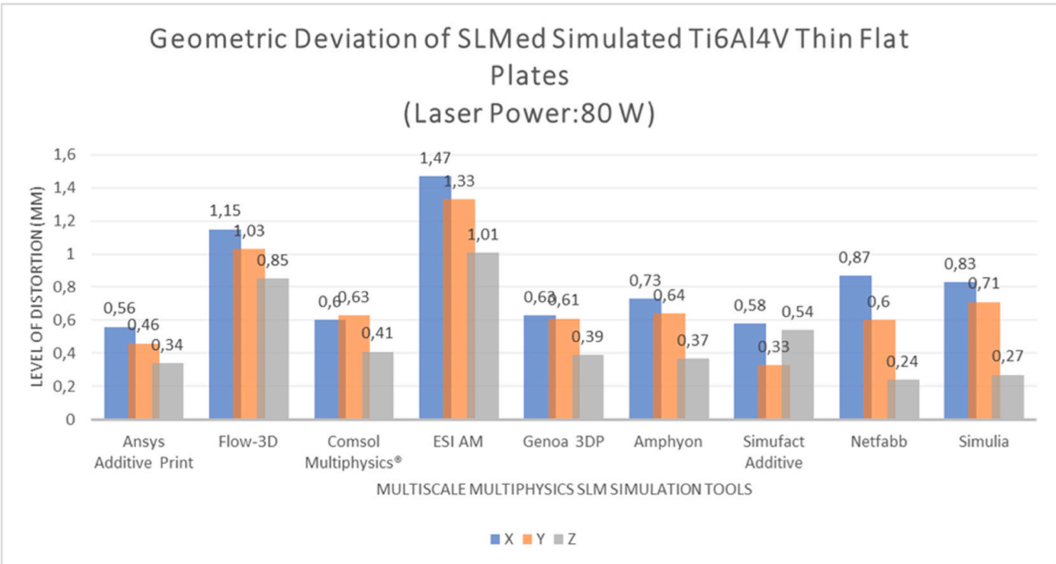


Fig. 15. Geometric deviation of SLMed simulated Ti6Al4V-thin flat plates (laser power: 80W) – A4.

b. Materials: Titanium alloy (Ti6Al4V) with a particle size of 30 μm was used. During the simulation phase, this material was selected from the simulation environment material database.
c. Built Specimens: Five specimens were built using the parameters presented in Table 2 – See Fig. 10. During the simulation phase, the specimen's geometry was generated in SolidWorks and subsequently imported into the simulation environments.

d. Laser Parameters: The experimental laser parameters are presented in Table 2 below.

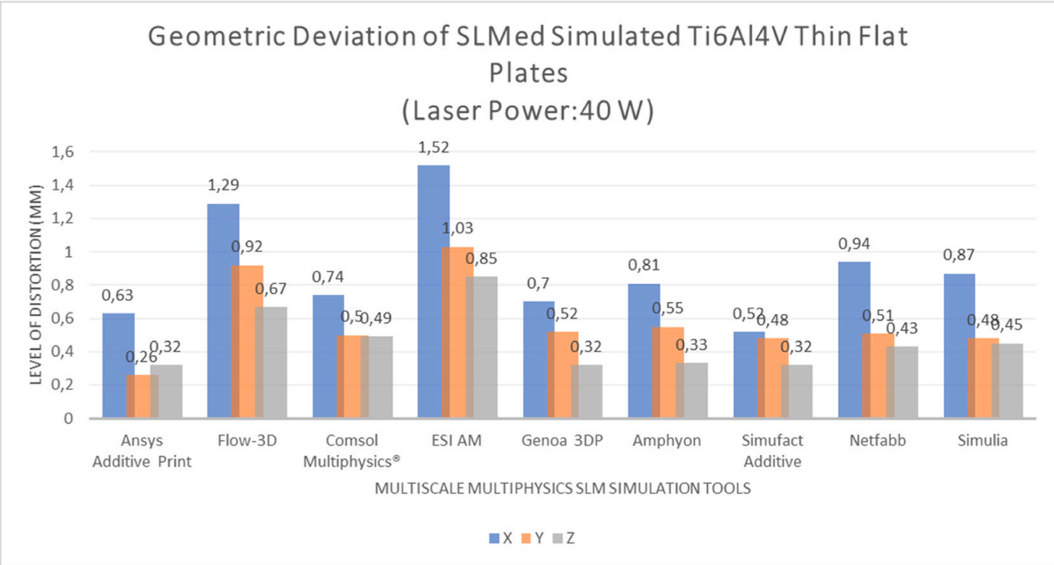
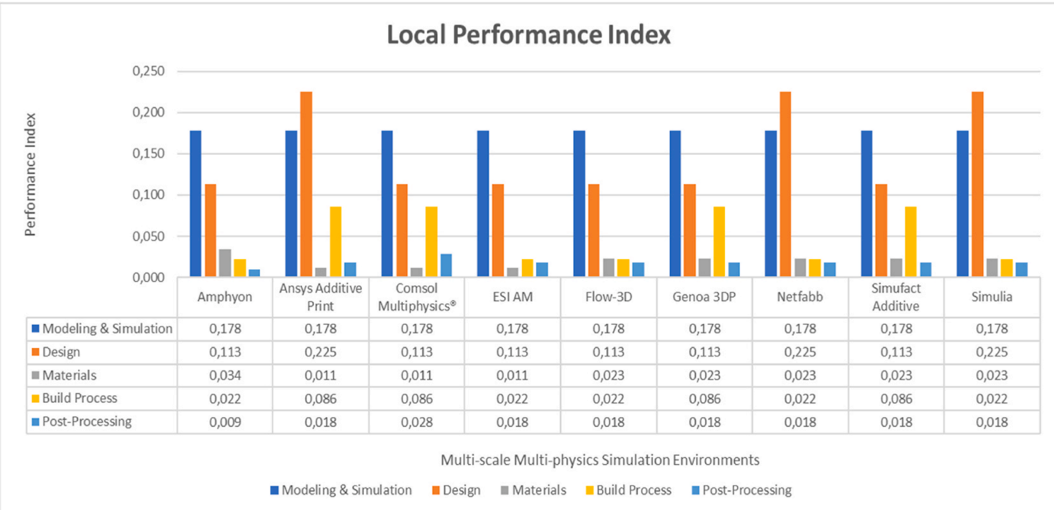


Fig. 16. Geometric deviation of SLMed simulated Ti6Al4V- thin flat plates (laser power: 40W) – A5.



	Amphyon	Ansys Additive Print	Comsol Multiphysics®	ESI AM	Flow-3D	Genoa 3DP	Netfabb	Simufact Additive	Simulia
Modeling & Simulation	0,178	0,178	0,178	0,178	0,178	0,178	0,178	0,178	0,178
Design	0,113	0,225	0,113	0,113	0,113	0,113	0,225	0,113	0,225
Materials	0,034	0,011	0,011	0,011	0,023	0,023	0,023	0,023	0,023
Build Process	0,022	0,086	0,086	0,022	0,022	0,086	0,022	0,086	0,022
Post-Processing	0,009	0,018	0,028	0,018	0,018	0,018	0,018	0,018	0,018

Fig. 17. Benchmarking of multi-scale multiphysics SLM simulation environments local performance indices.

e. Dimensional Distortion Measurement: This experiment's geometries are solely on the outside surface. Therefore, a Cartesian 3-dimensional Coordinate Measurement Machine (CMM) measures geometric deviations.

4. Results

4.1. Effectiveness of multi-scale multiphysics simulation environments

4.1.1. SWOT Analysis Matrix

Table 3 summarises the literature review findings in Section 2.4. in a SWOT Analysis Matrix. Additional data was also collected from the DoE phase and websites of the software provider [31–39].

The SWOT Analysis Matrix shows that each Simulation Environment should be used because of a particular end goal. Where Modelling and Simulation are the objectives, all simulation environments reviewed in this study can be used. Whereas design is the end goal, Ansys Additive Print, Autodesk Netfabb, and Simulia should be used. For materials testing or exploration, Amphyon should be used. Ansys Additive Print, Comsol Multiphysics, Genoa 3DP, and Simufact Additive should be used for the Build Process. While Comsol Multiphysics should be used for comprehensive post-processing. However, If the goal is to replicate an SLM process holistically,

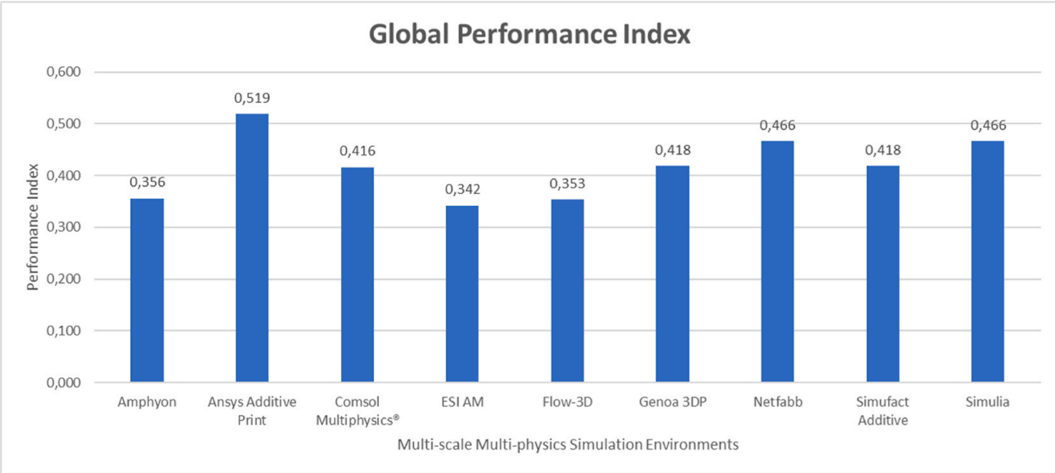


Fig. 18. Benchmarking of multi-scale multiphysics SLM simulation environments Global performance indices.

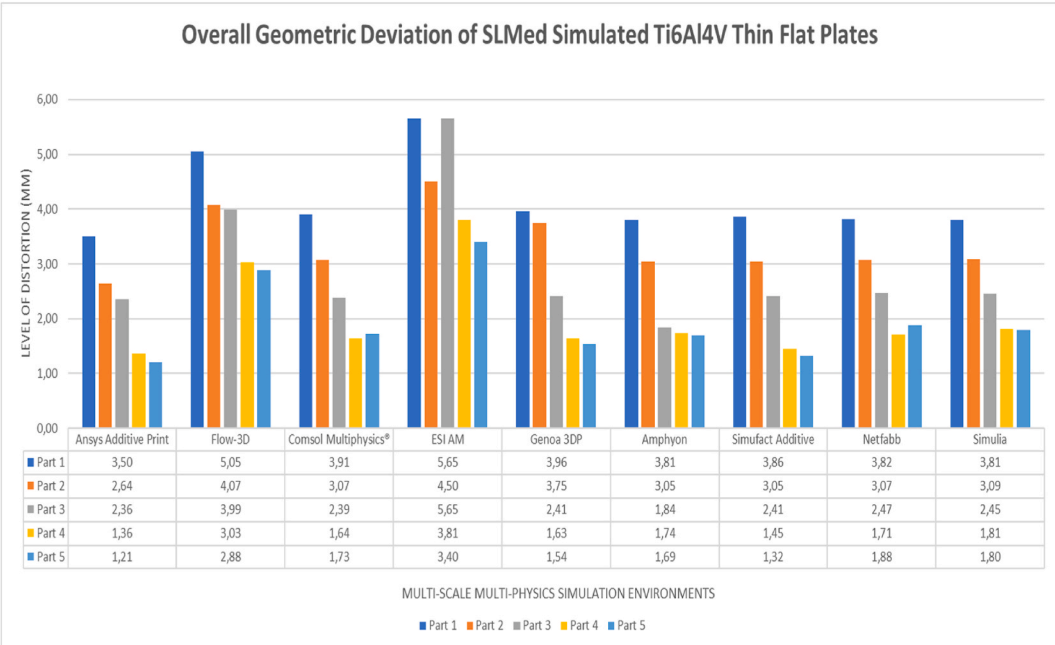


Fig. 19. Overall geometric deviation of SLMed simulated Ti6Al4V-thin flat plates.

Ansys Additive Print, Comsol Multiphysics, Genoa 3DP, Autodesk Netfabb, Simufact Additive, and Simulia are the most suitable simulation environments.

4.1.2. ANP model - performance measurement

The performance of Multi-scale Multiphysics Simulation Environments is presented quantitatively in Table 4. Priority rates are derived from the bibliometric analysis (See Fig. 8), and the degree of achievement is drawn from the SWOT analysis using the Cheng et al. [26] Scale (0–1). Equations presented under Section 3.2.3 are used to calculate local and Global Performance Indices, respectively. Results from the Performance Index Matrix show that Ansys Additive Print, Autodesk Netfabb, Simulia, Genoa 3DP, Simufact Additive, and Comsol Multiphysics are the highest-scoring environments, respectively.

4.2. Reliability of multi-scale multiphysics simulation environments

Using the process parameters presented in Table 2, five specimens were built to assess the capability of Multi-scale Multiphysics

Simulation Environments to provide reliable tools for the SLM process. Fig. 11 presents the five SLMed specimens with different laser power intensities. It is worth noting that specimen A5 did not fully form due to the low Energy Density (22 J/mm^3).

These specimens were reproduced in Multi-scale Multiphysics Simulated Environments using parameters defined in section 3.2.5. The distortion was measured in x, y, and z directions. Figs. 12–16 illustrate the results of this study. Fig. 12 shows a Distortion of SLMed simulated Ti6Al4V-thin flat plates at 200 W. From the data presented, the lowest deviations are in the x-x-direction with a minimum of 0.01 mm and a maximum of 0.28 mm. The highest deviations are observed in the y-direction, with a minimum of 3.22 mm and a maximum of 4.78 mm. Fig. 13 shows a Distortion of SLMed simulated Ti6Al4V-thin flat plates at 160 W. From the data presented; the lowest deviations are in the y-direction with a minimum of 0.02 mm and maximum of 0.08 mm. The highest deviations are observed in z-direction, with a minimum of 2.21 mm and a maximum of 3.56 mm. Fig. 14 shows a Distortion of SLMed simulated Ti6Al4V-thin flat plates at 130 W. From the data presented, the lowest deviations are in the x-direction with a minimum of 0.01 mm and a maximum of 0.46 mm. The highest deviations are observed in the y-direction, with a minimum of 1.82 mm and a maximum of 3.11 mm. Fig. 15 shows the Distortion of SLMed simulated Ti6Al4V-thin flat plates at 80 W. From the data presented, the lowest deviations are in the z-direction with a minimum of 0.34 mm and a maximum of 1.01 mm. The highest deviations are observed in the x-direction, with a minimum of 0.56 mm and a maximum of 1.47 mm. Fig. 16 shows the Distortion of SLMed simulated Ti6Al4V-thin flat plates at 40 W. From the data presented, the lowest deviations are in the z-direction with a minimum of 0.32 mm and a maximum of 0.85 mm. The highest deviations are observed in the x-direction, with a minimum of 0.63 mm and a maximum of 1.52 mm.

5. Discussion

5.1. Effectiveness of multi-scale multiphysics simulation environments

The Local Performance Indices of Multi-scale Multiphysics SLM Simulation Environments are presented in Fig. 17. From this representation, Modelling and Simulation's Performance Indices for all environments are optimal, with an average Performance Indices of 0.178. It was also evident that simulation environments performed differently based on various capabilities. Based on design capabilities, Ansys Additive Print, Autodesk Netfabb, and Simulia recorded the highest Local Performance Indices (0.225). Amphyon provides greater material capabilities, while Ansys Additive Print, Comsol Multiphysics, Genoa 3DP, and Simufact Additive provide comprehensive end-to-end build processes (Performance Indices of 0,086). The post-processing capability of Comsol Multiphysics is the most optimal, with a Performance Index of 0,028. However, it is imperative to note that the simulation software features assessed in this work are based on the versions available during the study.

Global Performance Indices of Multi-scale Multiphysics SLM Simulation Environments are presented in Fig. 18. From this illustration, it is evident that Ansys Additive Print, Autodesk Netfabb, Simulia, Genoa 3DP, Simufact Additive, and Comsol Multiphysics are the most effective Multi-scale Multiphysics SLM Simulation Environments, respectively.

5.2. Experimental validation

Fig. 19 shows the overall geometric deviations recorded through the experimental validation. Ansys Additive Print, Simufact Additive, Amphyon, Comsol Multiphysics, Autodesk Netfabb, and Simulia are the most reliable systems, respectively, as they generate the smallest deviations in predicting part distortion. It can also be observed that as laser power is increased, the mean deviation increases. Hence, observed deviations are lowest in A5 and highest in A1.

5.3. SLM advantages in the reviewed simulation environments

The simulation environments presented eliminate trial and error, and the SLM process is moved to a more cost-effective model. SLM's advantages in each Simulation Environment are summarised and compared in the following paragraphs.

Ansys Additive Print provides the lowest deflections in predicting distortion of SLM processes. Moreover, it provides complete SLM functionality from pre-to post-processing. Ansys can also predict porosity, residual stress, thermal behaviour, and mechanical properties. Flow-3D, On the other hand, stands out by providing a robust environment for CFD. FLOW-3D can predict can also predict porosity, and mechanical properties. While Comsol Multiphysics predicts distortion of SLM processes with low deviations, it offers complete SLM functionality from pre-to-post-processing capabilities. Moreover, it provides strong simulation modelling capabilities via features such as Continuous Modelling, Motion Modelling, Stochastic Modelling, Design Analysis, and Mesh Generation. Comsol can also predict porosity, residual stress, mechanical properties, and thermal behaviour.

ESI Additive Manufacturing offers access to comprehensive additive manufacturing experimental data, which sets it apart from other simulation environments. A strong Modelling and Simulation capability is provided by Genoa 3DP, which also provides complete SLM capabilities from pre-to post-processing. The support of external mesh from FEA software and the ability to simulate environmental effects provides a progressive failure modelling and analysis approach. ESI can also predict porosity, residual stress, thermal behaviour, and mechanical properties. Deflections are also relatively low in Amphyon's prediction of SLM outcomes, and more importantly, it provides a comprehensive material database. Amphyon can also predict porosity, residual stress, thermal behaviour, and mechanical properties. Moreover, Amphyon provides direct equipment selection capabilities. Simufact Additive also allows keeping deviations to a minimum in SLM outcome prediction. It also offers complete SLM functionality from pre-processing through post-processing. Like Comsol, it provides a comprehensive post-processing process (although not as advanced). Furthermore, it offers access to experiment data through partnerships with leading organisations in additive manufacturing. Simufact can also predict porosity, residual stress, thermal behaviour, and mechanical properties through a combination of process-based simulation and material models. Additionally, Simufact provides direct equipment selection capabilities.

Autodesk Netfabb also provides low deviations when predicting the outcome of the SLM process. Netfabb enables the direct import of many CAD files (no conversion errors). It provides design enhancement, manufacturing preparation, and building simulation tools in one package. Netfabb can also predict porosity, and mechanical properties. Simulia also shows low deflections in predicting outcomes of SLM processes. It enables the creation, instantiation, and running of simulation templates. The Eigenstrain method and voxel-based meshes are used in Simulia to simplify complex geometries. It is compatible with SolidWorks. It allows static testing. The mesh quality displayed by Simulia is satisfactory. The Dassault Systèmes digital platform allows collaboration with the world's leading digital manufacturers. Simulia can also predict porosity, residual stress, thermal behaviour, and mechanical properties.

5.4. Robust multi-scale multiphysics simulation environments

Effectiveness and Reliability measurement approaches show that Ansys Additive Print, Simufact Additive, Comsol Multiphysics, Autodesk Netfabb, and Simulia are the most robust SLM process simulation modelling systems, with Ansys Additive Print at the top of the list.

6. Conclusion

This paper evaluates Multi-scale Multiphysics SLM Simulation Environments regarding effectiveness and reliability. The effectiveness of simulation environments was assessed through SWOT-ANP analysis based on five key capabilities: Modelling and Simulation, Design, Materials, Build Process, and post-processing. Using the SWOT-ANP method, it is possible to compensate for the lack of a systematised method for quantifying the performance of evaluated factors in SWOT analysis. In contrast, the reliability of simulation environments was evaluated by their ability to predict SLMed parts with minimal deviation. This was accomplished using OFAT DoE, which measured geometric deviation on SLMed parts subjected to varying laser power intensities.

To achieve the objectives of this study, a twofold approach was followed. First, the effectiveness of Multi-scale Multiphysics SLM Simulation Environments was measured based on a comprehensive bibliometric analysis and literature review. As a preliminary step in building a robust database, a literature review using a simple, well-structured, and replicable methodology was used to find 110 articles in online scientific databases describing the application of Multi-scale Multiphysics Simulation Tools in SLM. By using bibliometric data, research clusters were formed. After collecting the data, the second step was to analyse the publication trend on the topic using charts and tables and identify the prominent Multi-scale Multiphysics SLM Simulation Environments and costs. A third step in the evaluation was to identify the areas of application of simulation environments and their frequency of use in the literature over the past two decades.

From the bibliometric data gathered it was concluded that Ansys Additive Print, Flow-3D, Comsol Multiphysics, ESI Additive Manufacturing, Genoa 3DP, Amphyon, Simufact Additive, Autodesk Netfabb, and Simulia have been the most prominent Multi-scale Multiphysics Simulation Environments over the past decades. It was also determined that Comsol Multiphysics was the least costly system in the long run. From the data gathered through the preliminary steps, the SWOT-ANP model developed in this study quantifies the performance of the prominent Multi-scale Multiphysics SLM Simulation Environments. The model is divided into five steps. Firstly, SWOT analysis identifies the strengths, weaknesses, opportunities and threats based on the pre-defined capabilities. Secondly, Degree of Achievement – Determination of the degrees of achievement of the SWOT factors with a 0–1 scale. The third step involves determining the priority of each capability based on the results of the literature review and biometric analysis. The fourth step is Local Performance Index determination using Equation (1) to determine each capability's Performance Index. Lastly, Global Performance Index - Determining the Performance Index for each Multi-scale Multiphysics SLM Simulation Environment - Equation (2). As a result of this study, it can be concluded that.

a. Modelling and Simulation - Modelling and Simulation capabilities are robust in all investigated Multi-scale Multiphysics SLM Simulation Environments.
b. Design - Ansys Additive Print, Autodesk Netfabb, and Simulia provide the most robust design capability.
c. Materials - Amphyon provides a larger material capability.
d. Build Process – Ansys Additive Print, Comsol Multiphysics, Genoa 3DP, and Simufact Additive provide the most robust Build Process.
e. Post-Processing - Comsol Multiphysics provides the most robust post-processing capability.

It was therefore determined, based on their Global Performance Indices, that Ansys Additive Print (0.519), Autodesk Netfabb (0.466), Simulia (0.466), Genoa 3DP (0.418), Simufact Additive (0.418), and Comsol Multiphysics (0.416) are the most effective currently available Multi-scale Multiphysics Simulation Environments for SLM applications. The last phase of this work's two-part approach focused on assessing the reliability of Multi-scale Multiphysics SLM Simulation Environments. This was achieved through an OFAT DoE, which measured geometric deviation on SLMed parts subjected to varying laser power intensities. Five specimens were built at different laser powers (200 W, 160 W, 130 W, 80 W, and 40 W) while maintaining other process parameters constant. These specimens were then replicated in the simulation environments of interest. The experimental results across all SLMed parts demonstrated that Additive Print (11.07 mm), Simufact Additive (12.09 mm), Amphyon (12.13 mm), Comsol Multiphysics (12.74 mm), Autodesk Netfabb (12.95 mm), and Simulia (12.96 mm) are the most reliable currently available Multi-scale Multiphysics Simulation

Environments for SLM applications.

This study marks a pioneering endeavour, offering a comprehensive quantitative assessment of Multi-scale Multiphysics Simulation Environments' performance—an unprecedented venture in its domain. Through a diligent SWOT-ANP analysis and empirical observations, the study conclusively identifies Ansys Additive Print, Simufact Additive, Comsol Multiphysics, Autodesk Netfabb, and Simulia as the most resilient systems for simulating the SLM process. Notably, Ansys Additive Print emerges as a cost-effective leader among these, further underlining its prominence to accurately predict part distortion. Intriguingly, the study observes an augmented discrepancy between simulated and actual parts as laser power levels escalate. This leads to a significant inference: prevailing Multi-scale Multiphysics SLM Simulation Environments grapple with accurately replicating outcomes within high temperature environments.

Pivotal factors lie at the core of these simulation environments' efficacy in SLM simulation. Their accuracy and robustness largely stem from deeply entrenched and rigorously validated mathematical models. Additionally, the seamless integration of Multiphysics capabilities stands as a cornerstone, harmoniously uniting diverse physics domains—thermal dynamics, fluid mechanics, solid mechanics, and material behaviour. This integration facilitates an all-encompassing understanding of the SLM process. Accurately representing material properties and behaviours is equally critical, encapsulating vital facets such as phase transformations, thermal conductivity, specific heat, and stress-strain responses. The meticulous portrayal of these aspects assumes paramount importance, ensuring the precision and dependability of the simulations.

Turning attention to computational speed, Ansys Additive Print, Simufact Additive, and Simulia exhibit remarkable efficiency owing to their adept solvers and parallel processing capabilities. These tools deliver accelerated simulations, particularly when harnessed alongside high-performance computing (HPC) resources, presenting a notable edge over other scrutinised alternatives. However, in practice, the computational pace for a specific simulation is subject to variation, contingent on factors such as model complexity, mesh size, and the available computational resources, encompassing CPU cores and RAM.

7. Future research

The following areas for future research have been identified.

a. Evaluate the effectiveness and reliability of Multi-scale Multiphysics SLM Simulation Modelling Environments at the nanoscale level.
b. Evaluate the effectiveness and reliability of Multi-scale Multiphysics SLM Simulation Modelling Environments based on porosity, residual stress, thermal behaviour, and mechanical properties prediction capabilities.

8. Limitations of the study

The following limitations have been identified.

a. The study is based on a literature review, which means that it is limited by the quality and quantity of the research that has been available on the topic (2000–2021).
b. The study focuses on a specific type of additive manufacturing process, SLM. The study's findings may not be generalisable to other additive manufacturing processes.
c. The study does not include a comprehensive evaluation of all the available Multi-scale Multiphysics Simulation Environments, as it only focuses on the prominent systems available. The study's findings may not represent all the available options.
d. This study does not assess the accuracy or reliability of the numerical models of SLM processes implemented in the evaluated Multi-scale Multiphysics Simulation Environments. Instead, the study focuses on evaluating the effectiveness and reliability of the simulation environments themselves.
e. The performance of the understudy simulation environments in predicting porosity, residual stress, thermal behaviour, and mechanical properties is not assessed in this study, as the focus is solely on part distortion.

Data Availability

Data associated with this study has not been deposited into any publicly repository. All data relevant to this study has included in article. For any additional data requirements beyond what is presented, we are more than willing to provide it upon request.

Funding

National Research Fund (NRF) Programme in which the grant was awarded: NRF Freestanding, Innovation and Scarce Skills Development Master's and Doctoral Scholarships (Grant UID: 130158).

CRediT authorship contribution statement

Thierry Abedi Mukalay: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Johan Alfred Trimble:** Supervision. **Khumbulani**

Mpofu: Supervision. **Rumbidzai Muvunzi:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A
–Summary of Literature review

SIMULATION TOOL	AUTHORS	YEAR	SUMMARY OF FINDINGS
Ansys Additive Print	Roberts et al. [40]	2009	The authors used Ansys to simulate the temperature field during laser melting of metal powders in additive layer manufacturing. The results showed that Ansys was able to accurately predict the temperature field in the SLM process.
	Li et al. [41]	2009	The authors used Ansys to study the effects of processing parameters on the temperature field of selective laser melting (SLM) metal powder. The results showed that Ansys was able to accurately predict the temperature field in SLM parts.
	Zhang et al. [42]	2010	The authors used Ansys to simulate the SLM of W–Ni–Fe powders. The results showed that Ansys was able to accurately predict the microstructure and properties of the SLM parts. The authors found Ansys to be a satisfactory software for simulating the SLM of W–Ni–Fe powders.
	Zaeh and Branner [43]	2010	The authors used Ansys to investigate the residual stresses and deformations in SLM parts. The results showed that Ansys was able to accurately predict the residual stresses and deformations in SLM parts.
	Contuzzi et al. [44]	2011	The authors used Ansys to perform a 3D finite element analysis (FEA) of the SLM process. The results showed that Ansys was able to accurately predict the temperature field, stress distribution, and deformation in SLM parts.
	Zhang et al. [45]	2011	The authors used Ansys to simulate the temperature field in SLM of PA6/Cu composite powders. Ansys was able to simulate the temperature field in SLM on PA6/Cu composite powders.
	Song et al. [46]	2011	The authors used Ansys to select process parameters for SLM of Ti6Al4V. Ansys was able to select process parameters for selective laser melting of Ti6Al4V based on temperature distribution simulation and experimental sintering.
	Liu et al. [24]	2012	The authors used Ansys to perform a micro scale 3D FEA of thermal evolution within the porous structure in SLM. Ansys was able to perform micro scale 3D FEM simulation on thermal evolution within the porous structure in SLM.
	Yin et al. [47]	2012	The authors used Ansys to simulate the temperature distribution in a single metallic powder layer for laser micro-sintering. Ansys was able to simulate the temperature distribution in single metallic powder layer for laser micro-sintering.
	Papadakis et al. [48]	2012	The authors used Ansys to perform a numerical simulation of the heat effects during thermal manufacturing of aero engine components. Ansys was able to numerically model the heat effects during thermal manufacturing of aero engine components.
	Krol et al. [49]	2013	The authors used Ansys to verify the results of structural simulations of metal-based additive manufacturing by means of neutron diffraction. Ansys was able to verify the structural simulation results of metal-based additive manufacturing by means of neutron diffraction.
	Hussein et al. [50]	2013	The authors used Ansys to simulate the temperature and stress fields in single layers built without-support in selective laser melting. Ansys was able to simulate the temperature and stress fields in single layers built without-support in selective laser melting.
	Keller and Ploshikhin [51]	2014	The authors developed a new method for fast predictions of residual stress and distortion of SLMed parts. Ansys was able to develop a new method for fast predictions of residual stress and distortion of SLMed parts.
	Schilp et al. [52]	2014	The authors used Ansys to investigate the temperature fields during laser beam melting by means of process monitoring and Multi-scale process modelling. Ansys was able to investigate temperature fields during laser beam melting by means of process monitoring and Multi-scale process modelling.
	Li and Gu [53]	2014	The authors used Ansys to perform a parametric analysis of the thermal behaviour during selective laser melting additive manufacturing of aluminum alloy powder. Ansys was able to perform a parametric analysis of thermal behaviour during selective laser melting additive manufacturing of aluminum alloy powder.
	Schoinochoritis et al. [54]	2015	The authors conducted a critical review of the simulation of SLM processes with the finite element method. The review showed that Ansys can be used to simulate the temperature distribution, residual stresses, and distortion in SLM processes.
	Afazov et al. [55]	2017	The authors developed a method for predicting and compensating for distortion in selective laser melting. The method was based on the finite element method and was able to predict the distortion of selective laser melting parts with a high degree of accuracy.
	Jankovics et al. [56]	2018	The authors used Ansys to perform topology optimization for SLM of structural components. The results showed that Ansys was able to generate topology-optimized designs for SLM with a high degree of accuracy.

(continued on next page)

Table A (*continued*)

SIMULATION TOOL	AUTHORS	YEAR	SUMMARY OF FINDINGS
	Ansari et al. [57]	2019	The authors used Ansys to create a numerical model of the SLM process. The model was validated by comparing the predicted temperature distribution and melting pool size to experimental measurements. The model was then used to investigate the effects of various process parameters on the temperature distribution and melting pool size.
	Cheng et al. [58]	2019	The authors developed a multi-scale modelling framework for simulating residual deformation in SLM parts. They found that Ansys was able to accurately predict the residual deformation in parts with simple geometries. However, Ansys was not able to accurately predict the residual deformation in parts with complex geometries.
	Barroqueiro et al. [59]	2019	The authors reviewed the SLM cycle in the aerospace industry. They found that Ansys is a commonly used tool for simulating SLM processes in the aerospace industry.
	Kumar and Narayan [60]	2020	The authors tested the tensile strength 3D printed PLA specimens and compared the results to the predictions of Ansys. They found that Ansys was able to accurately predict the tensile strength of the specimens.
	Mayer et al. [17]	2020	The authors simulated residual deformation in metal parts made by SLM. They found that Ansys was able to accurately predict the residual deformation in the parts.
	Song et al. [61]	2020	The authors developed a new method for predicting residual stresses in metal parts made by SLM. They found that their method was more accurate than Ansys in predicting the residual stresses in the parts.
	Peter et al. [31]	2020	The authors benchmarked build simulation software for SLM. They found that Ansys was one of the most accurate software packages for predicting the build time and quality of SMLed parts.
	Sahini et al. [62]	2020	The authors optimized the design of SLM processes using Ansys. They found that Ansys was able to help them to reduce the cost and improve the quality of the parts they were manufacturing.
	Nieto et al. [63]	2021	The authors used Ansys to design a 3D printed prosthetic hand. They found that Ansys was able to help them to create a design that was both functional and aesthetically pleasing.
	Loginov et al. [64]	2022	The authors investigated the compression deformation and fracture behaviour of SLMed Ti6Al4V cellular structures. They found that Ansys was able to accurately predict the behaviour of the structures.
Flow – 3D	Chandorkar and Palit [65]	2009	The authors used Flow-3D to simulate the dynamics of droplets in microfluidic devices. They found that Flow-3D was able to accurately predict the movement and breakup of droplets, as well as the mixing of fluids.
	Gabi et al. [23]	2015	The author used Flow-3D to simulate an avalanche impact into a reservoir. They found that Flow-3D was able to accurately predict the flow of water and sediment, as well as the resulting erosion and deposition.
	ArkanIbrahimi et al. [66]	2016	The authors used Flow-3D to simulate sediment transport and scouring downstream of perforated hump step broad crested weirs. They found that Flow-3D was able to accurately predict the flow of water and sediment, as well as the resulting scour depth.
	Dawoodjasim and Yuce [67]	2017	The authors compared the results of Flow-3D simulations to laboratory measurements of flow in a channel. They found that Flow-3D was able to accurately predict the flow velocity and pressure distribution.
	Barroqueiro et al. [59]	2019	The authors used Flow-3D to simulate the SLM of a variety of aerospace components, including brackets, gears, and turbine blades. They found that Flow-3D was able to accurately predict the temperature distribution, the flow pattern, and the mechanical properties of the SLMed parts
	Sahini et al. [62]	2020	The authors used Flow-3D to simulate the flow of molten metal during the SLM process. They found that Flow-3D was able to accurately predict the temperature distribution and the flow pattern of the molten metal.
	Rajaa and Kamel [68]	2020	The authors compared the performance of Flow-3D and Fluent-2D in simulating the flow pattern over an ogee spillway. They found that Flow-3D was able to predict the flow velocity and pressure distribution more accurately.
COMSOL Multiphysics®	Kruth et al. [69]	2012	The author used COMSOL Multiphysics to assess and compare the influencing factors of residual stresses in SLM. They found that the process parameters, the scanning strategy, and the material properties all have a significant impact on the residual stresses. They also found that the use of a cooling fluid can help to reduce the residual stresses.
	Gerlich et al. [70]	2013	The authors validated COMSOL Multiphysics as a simulation software for heat transfer calculation in buildings. They compared the results of COMSOL Multiphysics simulations to experimental data and found that the simulations were in good agreement with the experimental data.
	Lacatus et al. [71]	2015	The authors used COMSOL Multiphysics to simulate the dynamic thermal fields during the SML of biocompatible Ti-alloy. They found that the simulations were able to accurately predict the temperature distribution and the cooling rates.
	Chang [72]	2015	The author provides a comprehensive overview of rapid prototyping, including a discussion of the different AM processes and the challenges of AM. He also discusses the role of simulation in AM and the benefits of using COMSOL Multiphysics for AM simulation.
	Bikas et al. [73]	2016	The paper reviews the different methods and modelling approaches that have been used to simulate additive manufacturing (AM) processes. The authors found that there is no single, universally accepted method for simulating AM processes, and that the choice of method depends on the specific process and application. The authors found that COMSOL is a multiphysics software tool that allows users to create custom models that can simulate the interactions between different physical phenomena.

(*continued on next page*)

Table A (*continued*)

SIMULATION TOOL	AUTHORS	YEAR	SUMMARY OF FINDINGS
	Anagnostopoulos et al. [74]	2017	The authors used COMSOL Multiphysics to model the thermal performance of a solid-gas separation process (SGSP). They found that the simulations were able to accurately predict the temperature distribution and the pressure drop.
	Ngoveni et al. [75]	2019	The authors used COMSOL Multiphysics to model the residual stresses in Ti6Al4V ELI additive manufactured by laser engineered net shaping (LENS). They found that the simulations were able to accurately predict the residual stresses.
	Zhang et al. [76]	2019	The authors review the recent progress in the simulation of microstructure evolution in titanium alloys. The authors found that COMSOL Multiphysics was satisfactory for simulating microstructure evolution in SLM of titanium alloys
	Basu et al. [77]	2019	The authors used COMSOL Multiphysics to simulate the Ti6Al4V SLM using coupled physically based flow stress and metallurgical model. They found that the simulations were able to accurately predict the mechanical properties of the printed parts.
	Sahini et al. [62]	2020	The authors used COMSOL Multiphysics to optimize the SLM process for the manufacturing of a turbine blade. They found that the simulations were able to identify the optimal process parameters for manufacturing the turbine blade. They also found that the simulations could be used to predict the performance of the turbine blade.
	Wijayanti et al. [78]	2021	The authors used COMSOL Multiphysics to model the pyrolysis process with thermal effects. They found that the simulations were able to accurately predict the temperature distribution and the yield of the pyrolysis process. They also found that the simulations could be used to optimize the pyrolysis process to improve the yield of the process.
	Li and Butler [18]	2021	The authors used COMSOL Multiphysics to model the magnetotellurics process. They found that the simulations were able to accurately predict the electromagnetic fields generated by the magnetotellurics process.
	Kostin and Grygorenko [79]	2021	The authors used COMSOL Multiphysics to model the SLM process of products from HSLA Steel 09G2S. They found that the simulations were able to accurately predict the temperature distribution and the stress distribution during the additive process.
	Nieto et al. [63]	2021	The authors used COMSOL Multiphysics to perform topology optimization, finite element analysis, and process simulation for the design of a bicycle stem. They found that COMSOL Multiphysics was able to generate lightweight, strong, and stiff designs for the bicycle stem. They also found that COMSOL Multiphysics was able to predict the stress distribution and deformation of the SLMed parts accurately.
	Roopa et al. [25]	2021	The authors used COMSOL Multiphysics to model the triboelectric effect, the charge transport, and the electrical output of a TENG. They also used COMSOL Multiphysics to optimize the thickness of the flexible polymer used in the TENG. They found COMSOL Multiphysics to be a satisfactory tool for the modelling and simulation of triboelectric nanogenerators (TENGs).
ESI Additive Manufacturing	Sahini et al. [62]	2020	The authors used to simulate the SLM process for the production of a Ti6Al4V bracket. The authors found that ESI Additive Manufacturing was able to accurately predict the temperature distribution, residual stresses, and mechanical properties of the bracket. They also found that the software was easy to use and had a user-friendly interface.
GENOA 3DP	Mercelis and Kruth [80]	2006	GENOA 3DP was used to simulate the effects of residual stresses on the mechanical properties of parts produced by selective laser sintering (SLS) and selective laser melting (SLM). The results showed that residual stresses can cause warpage, cracking, and reduced strength in SLS and SLM parts. The authors found that the magnitude of residual stresses can be reduced by using a slower scanning speed and a lower laser power.
	Turk et al. [81]	2016	GENOA 3DP was used to simulate the AM process for a robotic arm. The results showed that GENOA 3DP was able to accurately predict the temperature distribution, residual stresses, and mechanical properties of the robotic arm.
	Talagani et al. [82]	2016	GENOA 3DP was used to simulate the AM process for a full-size car. The results showed that GENOA 3DP was able to accurately predict the temperature distribution, residual stresses, and mechanical properties of the car.
	Song [83]	2017	GENOA 3DP was used to model the residual stresses in thin wall buildups. The results showed that GENOA 3DP was able to accurately predict the residual stresses in thin wall buildups.
	Barroqueiro et al. [59]	2019	GENOA 3DP was not specifically used in this paper, but the authors found that it is a widely used software for the simulation of AM processes in the aerospace industry.
	Sahini et al. [62]	2020	GENOA 3DP was evaluated as part of a study on the use of simulation and optimization for SLM processes. The results showed that GENOA 3DP was able to accurately predict the temperature distribution, residual stresses, and mechanical properties of SLMed parts.
	Nieto et al. [63]	2021	GENOA 3DP was used to optimize the design of a bicycle stem for strength and stiffness. The results showed that GENOA 3DP was able to help the authors design a bicycle stem that was both strong and lightweight. The authors were satisfied with the results of the study, and they believe that GENOA 3DP is a valuable tool for the optimization of SLM designs.
	Brackett et al. [84]	2011	The authors proposed a topology optimization method for SLM. They used Amphyon to validate their method, and they found that Amphyon was able to accurately predict the stresses and deformations in SLM parts.
Amphyon	Neugebauer and Ploshikhin [85]	2013	The authors used Amphyon to simulate the thermo-mechanical behaviour of titanium aerospace structures during SLM. They found that Amphyon was able to accurately predict the temperature distribution, residual stresses, and deformations in the structures.
	Neugebauer et al. [86]	2014	The authors used Amphyon to calculate the distortion in SLM parts made of hardening stainless-steel. They found that Amphyon was able to accurately predict the distortion in the parts.

(*continued on next page*)

Table A (*continued*)

SIMULATION TOOL	AUTHORS	YEAR	SUMMARY OF FINDINGS
	Ferguson et al. [87]	2016	The authors reviewed the capabilities of topology optimization software for SLM. They found that Amphyon was one of the most capable software packages, and they were satisfied with the results of their review.
	Gouge and Michaleris [88]	2017	The authors presented a comprehensive overview of thermo-mechanical modelling of SLM. They cited Amphyon as one of the most popular software packages for SLM simulation.
	Barroqueiro et al. [59]	2019	The authors reviewed the metal SLM cycle in the aerospace industry. They found that Amphyon is a widely used software for the simulation of SLM processes in the aerospace industry.
	Peter et al. [31]	2020	The authors benchmarked six build simulation software packages for laser powder bed fusion of metals. They found that Amphyon was one of the most accurate software packages.
	Sahini et al. [62]	2020	The authors evaluated a number of SLM simulation software packages, including Amphyon. They found that Amphyon was able to accurately predict the temperature distribution, residual stresses, and mechanical properties of SLM parts. They also found that Amphyon was easy to use and had a user-friendly interface.
	Mayer et al. [17]	2020	The authors used Amphyon to simulate the residual deformations in SLMed parts. They found that Amphyon was able to accurately predict the residual deformations.
	Borovkov et al. [89]	2020	The authors proposed a method for improving the printing process stability and the geometrical accuracy of SLMed parts. They used Amphyon to validate their method, and they found that Amphyon was able to accurately predict the stresses and deformations in the parts.
	Elisel et al. [90]	2021	The authors evaluated a number of design support tools for SLM. They found that Amphyon was one of the most comprehensive tools, and they were satisfied with the results of their evaluation.
	Stiuso et al. [91]	2021	The authors experimentally assessed the compensated distortion in Ti6Al4V-SLMed parts. They used Amphyon to simulate the process, and they found that Amphyon was able to accurately predict the distortion in the parts.
	Nieto et al. [63]	2021	The authors found that Amphyon was particularly useful for the design of complex parts with internal features. The software was able to predict the stresses and deformations that would occur during the SLM process.
Simufact Additive	Jianhua et al. [92]	2010	The paper found that Simufact can be used to predict the temperature distribution, stress, and strain in plastic parts during machining. The paper also found that Simufact can be used to optimize the machining process for improved part quality.
	Zhang et al. [42]	2010	The paper found that Simufact Additive can be used to predict the temperature distribution, stress, and strain in W–Ni–Fe PBF parts during printing.
	Neugebauer et al. [86]	2014a	The paper presents a multi-scale finite element method (FEM) simulation for the calculation of distortion in SLM of hardening stainless steel. The paper presents a multi-scale finite element method (FEM) simulation for the calculation of distortion in SLM of hardening stainless steel.
	Neugebauer et al. [93]	2014b	The authors used Simufact Additive to simulate the SLM process of a Ti6Al4V alloy. The simulation results were compared with experimental results, and the results showed that the simulation was able to predict the temperature field, stress field, and microstructure of the workpiece with good accuracy.
	Hwang et al. [94]	2017	The paper found that Simufact Additive can be used to predict the temperature distribution, stress, and strain in metal SLM parts during printing.
	Afazov et al. [55]	2017	The authors used Simufact Additive to simulate the distortion of SLM parts made of Ti6Al4V. The simulation results were compared with experimental results for the distortion of the workpiece. The simulation results were found to be in good agreement with the experimental results.
	Wiberg et al. [95]	2018	The paper found that Simufact Additive can be used to optimize the AM process for a variety of properties, including strength, stiffness, and weight. The paper also found that Simufact Additive can be used to optimize the AM process for a variety of AM technologies, including SLM, PBF, and electron beam melting.
	Çelebi and Appavuravther [96]	2018	The paper found that the software can be used to predict the amount of residual stress that will occur during AM printing. The paper also found that Simufact Additive can be used to modify the SLM process parameters to reduce the amount of residual stress.
	Mezzadri et al. [97]	2018	The paper found that the software can be used to design support structures that are strong enough to support the SLMed part during printing, but that are also as light as possible. The paper also found that Simufact Additive can be used to optimize the placement of support structures to minimize the amount of residual stress in the SLM part.
	Sebastian et al. [98]	2018	The paper found that the software can be used to design parts that are strong enough to meet the required strength and stiffness requirements, but that are also as lightweight as possible. The paper also found that Simufact Additive can be used to optimize the placement of features in the SLMed part to minimize the amount of residual stress in the part.
	Seidel et al. [99]	2018	The paper found that the software can be used to predict the amount of distortion that will occur during SLM printing.
	Liang et al. [100]	2018	The paper found that the software can be used to predict the amount of residual stress that will occur in SLMed parts with complex geometries.
	Barroqueiro et al. [59]	2019	The paper does not mention the results of any specific studies that have been conducted using Simufact Additive. However, the paper does mention a number of software tools that can be used for SLM, including Simufact Additive.
	Wiberg et al. [101]	2019	The paper found that Simufact Additive has a user-friendly interface that makes it easy to use for both experienced and inexperienced users.
	Chang [102]	2019	They found that Simufact Additive was able to accurately predict the temperature distribution, residual stresses, and mechanical properties of the part. They also found that Simufact Additive

(*continued on next page*)

Table A (*continued*)

SIMULATION TOOL	AUTHORS	YEAR	SUMMARY OF FINDINGS
			was able to be used to optimize the SLM process parameters to reduce the amount of residual stress in the part.
	Ansari et al. [57]	2019	They found that Simufact Additive was able to accurately predict the temperature distribution and melting pool size during the SLM process.
	Cheng et al. [58]	2019	They found that Simufact Additive was able to accurately predict the residual stresses and deformation in SLMed parts. They also found that Simufact Additive was able to be used to optimize the SLM process parameters to reduce the amount of residual stress and deformation in the parts.
	Peter et al. [31]	2020	The authors benchmarked six build simulation software packages for SLM. They found that Simufact Additive was the most accurate and versatile build simulation software package. They also found that Simufact Additive was the most user-friendly build simulation software package.
	Sahini et al. [62]	2020	The authors optimized the design of SLM support structures using Simufact Additive. They found that Simufact Additive was able to accurately predict the strength and stiffness of SLM support structures.
	Allaire et al. [103]	2020	They found that Simufact Additive was able to accurately predict the residual stress in SLMed parts with support structures. They also found that Simufact Additive was able to be used to optimize the placement of support structures to reduce the amount of residual stress in the parts.
	Taufek et al. [104]	2020	The authors used Simufact Additive to analyse the distortion of a SLM part made of SS316L using the inherent strain method. They found that Simufact Additive was able to accurately predict the distortion of the part.
	Mayer et al. [17]	2020	The authors simulated and validated the residual deformations in SLM parts using Simufact Additive. They found that Simufact Additive was able to accurately predict the residual deformations in the parts.
	Song et al. [61]	2020	The authors found that Simufact Additive was able to accurately predict the residual stresses and distortion in complex metallic components made by SLM.
	Pagac et al. [104]	2021	The author found that Simufact Additive was able to accurately predict the distortion of SLMed parts made of stainless steel AISI 316L.
	Elisel et al. [90]	2021	The authors evaluated a number of design support tools for AM and found that Simufact Additive was the most comprehensive and user-friendly tool.
	Zhao et al. [105]	2021	The authors developed a new data processing system for Simufact Additive based on QT and MySQL. They found that the new system was able to improve the performance of Simufact Additive by reducing the time it takes to run simulations.
	Nieto et al. [63]	2021	The authors conducted a case study using Simufact Additive to design and optimize a SLMed part. They found that Simufact Additive was able to help them to design a part that was lighter, stronger, and more cost-effective than a traditionally manufactured part.
Netfabb	Wang and Kruth [106]	2000	The authors developed a simulation model for direct SLS of metal powders. The model was able to predict the temperature distribution, melt pool geometry, and solidification behaviour during SLS. The authors found that the model was able to accurately predict the results of SLS experiments.
	Kolossov et al. [107]	2004	The authors developed a 3D finite element (FE) simulation for temperature evolution in the SLS process. The model was able to predict the temperature distribution throughout the entire SLS build volume. The authors found that the model was able to accurately predict the results of SLS experiments.
	Chen et al. [108]	2010	The authors developed a numerical simulation of two-dimensional melting and re-solidification of a two-component metal powder layer in the SLS process. The model was able to predict the temperature distribution, melt pool geometry, and solidification behaviour during SLS. The authors found that the model was able to accurately predict the results of SLS experiments.
	Liu et al. [24]	2012	The authors developed a micro scale 3D FE simulation on thermal evolution within the porous structure in the SLS process. The model was able to predict the temperature distribution, melt pool geometry, and solidification behaviour within the porous structure of SLS parts. The authors found that the model was able to accurately predict the results of SLS experiments.
	Shen and Chou [109]	2012a	The authors developed a thermal modelling of electron beam additive manufacturing (EBAM) process-powder sintering effects. The model was able to predict the temperature distribution, melt pool geometry, and solidification behaviour during EBAM. The authors found that the model was able to accurately predict the results of EBAM experiments.
	Shen and Chou [110]	2012b	The authors investigated the effects of preheating on the thermal behaviour of electron beam additive manufacturing (EBAM). They used Autodesk Netfabb to simulate the EBAM process with and without preheating. The results showed that preheating can improve the quality of EBAM parts by reducing the thermal stresses and improving the mechanical properties.
	Shiqing [111]	2013	The authors used Autodesk Netfabb to simulate the wire temperature field during laser hot wire welding. The results showed that Autodesk Netfabb was able to accurately predict the wire temperature field, which can be used to improve the quality of laser hot wire welded joints.
	Strano et al. [112]	2013a	The authors developed a new approach to the design and optimization of support structures in additive manufacturing. The approach uses Autodesk Netfabb to generate support structures that are optimized for strength and weight.
	Strano et al. [113]	2013b	The authors investigated the effects of process parameters on surface roughness in selective laser melting (SLM). They used Autodesk Netfabb to simulate the SLM process with different process parameters. The results showed that Autodesk Netfabb was able to accurately predict the surface roughness of SLM parts.

(*continued on next page*)

Table A (*continued*)

SIMULATION TOOL	AUTHORS	YEAR	SUMMARY OF FINDINGS
	Kanada [114] Kanada [115]	2014a 2014b	The author developed a method for AM generative art by using combination and deformation of printing direction. The method used Autodesk Netfabb to generate the AM instructions for the generative art. The author developed a method for designing, partitioning, and printing parts with specified printing direction. The method used Autodesk Netfabb to generate the AM instructions for the parts.
	Kanada et al. [116]	2015	The authors developed a method for SLMed plates without support structures. The method uses Autodesk Netfabb to generate the SLM process instructions for the plates. The results showed that the method was able to successfully print plates without support structures.
	Ahuja et al. [117]	2015	The authors discussed the challenges and opportunities of additive manufacturing in production. They noted that Autodesk Netfabb is a popular software for additive manufacturing, but that it is not without its limitations. For example, Netfabb can be difficult to use for complex parts.
	Liu et al. [118]	2015	The authors used Autodesk Netfabb to simulate the thermal evolution within the porous structure in selective laser sintering (SLS). The results showed that Netfabb was able to accurately predict the temperature distribution and the evolution of the porous structure during SLS.
	Gouge et al. [119]	2015	The authors developed a model for forced convection in the thermal simulation of laser cladding processes. The model was implemented in Autodesk Netfabb and was used to simulate the thermal behaviour of a laser cladding process. The results showed that the model was able to accurately predict the temperature distribution and the evolution of the heat source during laser cladding.
	Belgiu et al. [120]	2015	The authors investigated the product management of making large pieces through Rapid Prototyping PolyJet® technology. They used Autodesk Netfabb to design and print a large piece using PolyJet® technology. The results showed that Netfabb was able to be used to design and print large pieces using PolyJet® technology.
	Nie et al. [121]	2016	The authors experimentally studied and modelled the deposition of H13 steel using laser hot-wire additive manufacturing. The experiments were conducted using a laser hot-wire additive manufacturing machine and the results were used to develop a model for the deposition process. The model was implemented in Autodesk Netfabb and was used to simulate the deposition process. The results showed that the model was able to accurately predict the temperature distribution and the evolution of the heat source during laser hot-wire additive manufacturing.
	Gouge et al. [88]	2017	The authors presented a comprehensive overview of thermo-mechanical modelling of additive manufacturing (AM). The book covers a wide range of topics, including heat transfer, fluid flow, solidification, and residual stress. Autodesk Netfabb is mentioned in the book as a software that can be used to simulate AM processes.
	Wiberg et al. [95]	2018	The authors proposed a topology optimization method for generating self-supporting support structures in SLM. The method was implemented in Autodesk Netfabb and was used to generate support structures for a variety of SLMed parts. The results showed that the method was able to generate support structures that were both effective and lightweight.
	Barroqueiro et al. [59]	2019	The authors reviewed the metal AM cycle in the aerospace industry. The review covered a wide range of topics, including process selection, design for AM, and post-processing. Autodesk Netfabb is mentioned in the review as a software that can be used to support all stages of the metal AM cycle.
	Wiberg et al. [101]	2019	The authors proposed an optimization framework for SLM given topology optimization results. The framework was implemented in Autodesk Netfabb and was used to optimize the design of a variety of SLMed parts. The results showed that the framework was able to improve the strength, stiffness, and manufacturability of SLMed parts.
	Bui et al. [122]	2019	The authors presented a finite element (FE) model for simulating SLM. The model was implemented in Autodesk Netfabb and was used to simulate the SLM process for a variety of materials. The results showed that the model was able to accurately predict the temperature distribution, melt pool geometry, and solidification behaviour during SLM.
	Peter et al. [31]	2020	The authors benchmarked a number of build simulation software for SLM. The software were evaluated based on their accuracy, ease of use, and cost. Autodesk Netfabb was one of the software evaluated and was found to be a satisfactory software for SLM.
	Sahini et. [62]	2020	The authors presented a review of optimization and simulation of SLM process. The review covered a wide range of topics, including process planning, design, and post-processing. Autodesk Netfabb is mentioned in the review as a software that can be used to support all stages of SLM process optimization and simulation.
	Elisel et al. [90]	2021	This paper evaluated a number of design support tools for SLM. The tools were evaluated based on their functionality, ease of use, and cost. Autodesk Netfabb was one of the tools evaluated and was found to be a satisfactory tool for SLM. However, the paper also noted that Netfabb could be improved by adding more functionality and by making the software more user-friendly.
	[123] Taylor et al.	2021	This paper proposed SLM qualification test artifact. The artifact was designed to be used to evaluate the quality of SLMed parts. Autodesk Netfabb was used to generate the build files for the artifact. The results showed that the artifact was able to be successfully 3D printed using SLM.
	Hatala et al. [124]	2021	This paper presented a thermo-mechanical analysis of laser hot wire additive manufacturing (LHWA) of nickel aluminide (NAB). The analysis was conducted using Autodesk Netfabb. The results showed that LHWA can be used to produce NAB parts with good mechanical properties.
	Nieto et al. [63]	2021	This paper reviewed a number of tools for design for SLM. The tools were reviewed based on their functionality, ease of use, and cost. Autodesk Netfabb was one of the tools reviewed and was found to be a satisfactory tool for SLM. However, the paper also noted that Netfabb could be improved by adding more functionality and by making the software more user-friendly.

(*continued on next page*)

Table A (*continued*)

SIMULATION TOOL	AUTHORS	YEAR	SUMMARY OF FINDINGS
Simulia	Jiang et al. [125]	2002	This paper used Simulia to perform a finite element analysis of residual stresses and deformations in SLM. The results showed that Simulia was able to accurately predict the residual stresses and deformations in SLMed parts.
	Zhang and Chou [126]	2006	This paper used Simulia to perform 3D finite element analysis of fused deposition modelling (FDM) process. The results showed that Simulia was able to accurately predict the temperature distribution, stress distribution, and deformation in FDM parts.
	Zhang and Chou [22]	2008	This paper used Simulia to perform a parametric study of part distortions in FDM. The results showed that Simulia was able to accurately predict the part distortions as a function of process parameters.
	Van Belle et al. [127]	2012	This paper compared the results of numerical simulations of SLM using different software packages, including Simulia. The results showed that Simulia was able to accurately predict the temperature distribution, stress distribution, and deformation in SLMed parts.
	Mukherjee et al. [128]	2014	This paper used Simulia to perform a three-dimensional heat transfer analysis of SLM process. The results showed that Simulia was able to accurately predict the temperature distribution in SLMed parts.
	Song et al. [129]	2015	This paper used Simulia to study the residual stresses and microstructure in SLM samples. The results showed that Simulia was able to accurately predict the residual stresses and microstructure in SLMed parts.
	Costa et al. [21]	2015	This paper investigated the effect of thermal conditions on heat transfer in FDM/FFE process. The results showed that Simulia was able to accurately predict the heat transfer in FDM/FFE process.
	Talagani et al. [130]	2015	The authors used Simulia to simulate the big area AM of a full-size car. The results showed that Simulia was able to accurately predict the temperature distribution, stress distribution, and deformation in the car. The authors found Simulia to be a satisfactory software for simulating large-scale AM projects.
	Parry et al. [131]	2016	The authors used Simulia to study the effect of laser scan strategy on residual stress in SLM. The results showed that the laser scan strategy has a significant impact on the residual stress in SLM parts. The authors found Simulia to be a satisfactory software for simulating the effects of process parameters on residual stress in SLM.
	Dunbar et al. [132]	2016	The authors experimentally validated a finite element methodology for predicting deformation in SLM using Simulia. The results showed that the finite element methodology was able to accurately predict the deformation in SLMed parts.
	Mukherjee et al. [133]	2017	This paper improved the prediction of residual stresses and distortion in SLM using Simulia. The results showed that the improved prediction method was able to predict the residual stresses and distortion more accurately in SLMed parts.
	Barroqueiro et al. [59]	2019	The authors reviewed the AM cycle in the aerospace industry. The authors found that Simulia is a widely used software for simulating the AM cycle in the aerospace industry. The authors found Simulia to be a satisfactory software for simulating the AM cycle in the aerospace industry.
	Wiberg et al. [101]	2019	The authors reviewed the available design methods and software for SLM. The authors found that Simulia is a widely used software for design for SLM. The authors found Simulia to be a satisfactory software for design for SLM.
	Zhang et al. [76]	2019	The authors reviewed the recent progress in the simulation of microstructure evolution in SLM of titanium alloys. The authors found Simulia to be a satisfactory software for simulating the microstructure evolution in SLM of titanium alloys.
	Yang et al. [134]	2019	The authors used Simulia to predict the residual strain in a SLM Inconel 625 single cantilever part. The results showed that Simulia was able to accurately predict the residual strain in the part.
	Bertini et al. [135]	2019	The authors used Simulia to predict the residual stress in SLMed parts. The results showed that Simulia was able to accurately predict the residual stress in the parts.
	Favaloro et al. [135]	2019	The authors used Simulia to simulate the AM of polymeric composites. The results showed that Simulia was able to accurately simulate the process.
	Sahini et al. [62]	2020	The authors used Simulia to optimize and simulate the SLM of various parts. The results showed that Simulia was able to help the authors optimize the process and improve the properties of the parts.
	Song et al. [61]	2020	The authors reviewed the recent advances in SLM process simulation, with a focus on residual stresses and distortion predictions in complex metallic components. The authors found that Simulia is one of the most advanced software packages for SLM process simulation.
	Gatsos et al. [20]	2020	The authors reviewed the recent advances in computational modelling of process-microstructure-property relationships in SLM. The authors found that Simulia is one of the most advanced software packages for computational modelling of SLM.
	Elisel et al. [90]	2021	This paper evaluated several design support tools for additive SLM. The paper found that Simulia was one of the most comprehensive and user-friendly design support tools for SLM. Simulia was found to be effective in supporting the design process, including the generation of design concepts, the validation of design concepts, the generation of manufacturing instructions, and the optimization of the design for SLM.
	Nieto et al. [63]	2021	The paper found that Simulia was one of the most comprehensive and user-friendly SLM tools. Simulia was found to be effective in supporting the design process, including the design for buildability, the design for material selection, and the design for post-processing.

Table B
A brief description of the mathematical methods of the compared simulation tools.

SIMULATION TOOL	MATHEMATICAL METHODS
Ansys Additive Print	Finite Element Analysis (FEA) for thermal, mechanical, and material behaviour modelling including heat transfer, solidification, and stress analysis.
Flow-3D	Computational Fluid Dynamics (CFD) for simulating fluid flow, heat transfer, and phase change during the SLM process, including melt pool dynamics and powder bed interactions.
Comsol Multiphysics	Finite Element Method (FEM) for multiphysics simulations integrating heat transfer, solid mechanics, and fluid flow to analyse thermal history, stress, and deformation during SLM.
ESI Additive Manufacturing	Combination of FEA and CFD for modelling thermal and fluid dynamics, predicting temperature distribution, melt pool formation, and stress-induced distortions during SLM.
Genoa 3DP	Finite Element Analysis (FEA) for thermal and mechanical analysis, predicting residual stress, distortion, and microstructure evolution in the printed part during the SLM process.
Amphyon	FEA combined with machine learning algorithms to optimize process parameters for SLM, focusing on thermal aspects, material behaviour, and improving build success rates.
Simufact Additive	Finite Element Method (FEM) to simulate the complete additive manufacturing process, including powder spreading, melting, and solidification, focusing on predicting distortions, residual stresses, and part quality.
Autodesk Netfabb	FEA for thermal and stress analysis, focusing on thermal gradients, solidification rates, and microstructure prediction to optimize printing strategies and reduce defects.
Simulia	FEM and FEA to simulate the entire SLM process, including thermal, mechanical, and metallurgical aspects, modelling thermal history, phase transformations, and stress evolution in the part.

Table C
Type Finite Element Analysis [136,137].

TYPE OF FEM	APPLICATIONS
Linear Static Stress Analysis	Factor of safety calculation, part & assembly stress analysis, deflection calculations, correlation to measurements of deflections and strains, contact stress computation, super-position of thermal stresses, stiffness calculations to achieve stated targets
Frequency & Buckling Analysis	Computation of frequencies & mode shapes, modal assurance criteria (MAC), correlation to measured data, buckling calculations for axially loaded members, critical speed calculations, Campbell diagram for rotor-dynamics, and point mobility analysis
Dynamic Analysis	Frequency response analysis, seismic analysis response calculations, harmonic analysis, random vibration calculations, dynamic stress computations, power train vibration analysis, and shock calculations
Non-Linear Analysis	Material non-linear analysis, geometric non-linear analysis, FEA of rubber & elastomers, non-linear dynamic analysis, time domain response analysis, impact analysis, thermo-mechanical analysis involving large displacements, and elasto-plastic deformation analysis
Analysis of Composites	Failure mode prediction of composite panels, filament wound composite – anisotropic material modelling, random fibre composites, stiffness, deflection and critical load calculation of composite structures, metal matrix composites – thermo mechanical analyses
Thermal Analysis	Thermal stress analysis of parts and assemblies, transient thermal analysis, thermo-mechanical analysis, coupled thermo-fluid analysis, natural and forced convection analysis, non-linear thermal analysis of curing processes, and creep analysis
Fatigue Analysis	Remaining life analysis (RLA), durability analysis, failure prediction analysis, high cycle fatigue calculations, correlation to real-world situations, comparison of alternate materials for extended life and warranty, life extension analysis.
CFD Fluid Flow Analysis	Pressure drop calculations, conjugate heat transfer analysis, electronic cooling analysis, thermal efficiency calculations, fluid flow simulation in devices, such as pumps, valves, ducts, piping networks, fans, diffusers, cyclones, blowers, heat exchangers, design optimization based on performance prediction
ASME Stress Analysis	Stress analysis per ASME (American Society of Mechanical Engineers) codes, nozzle stress analysis, stress intensity calculations, and shell & full-scale 3D stress analysis of pressure vessels, among others
Design Optimization	Optimization of CAD geometries, weight reduction analysis, value addition & value engineering analysis, sensitivity-based optimization, and optimization of design variables based on performance targets

References

[1] C. Yin, A. Mckay, Introduction to modelling and simulation techniques, in: The 12th China-Japan International Workshop on Information Technology and Control Applications (ITCA2018) Binjiang International Hotel, Tengzhou, Shandong, China, Nov. 2-6, 2018, 2018.

[2] N. Seekhao, C. Shung, J. Jaja, L. Mongeau, N.Y.K. Li-Jessen, Real-time agent-based modelling simulation with in-situ visualization of complex biological systems: a case study on vocal fold inflammation and healing, in: IEEE International Symposium on Parallel & Distributed Processing - Workshops and PhD Forum. April 5, 2016, pp. 463–472.

[3] E.F. Frazier, F. Mater, Metal additive manufacturing: a review, J. Mater. Eng. Perform. 23 (2014) 1917–1928.

[4] P. Nath, Z. Hu, S. Mahadevan, Solid freeform fabrication, Int. J. Adv. Manuf. Technol. (May 10) (2017) 7–9.

[5] Z. Hu, S. Mahadevan, Uncertainty quantification and management in additive manufacturing: current status, needs, and opportunities, Int. J. Adv. Manuf. Technol. 93 (2017) 2855–2874. Oct.

[6] Lindgren L.E., Lundbäck A., Fisk M., Pederson R., Andersson J., Simulation of additive manufacturing using coupled constitutive and microstructure models, Addit. Manuf. 12 (2016) Jan 12: 144–158.

[7] T. Mukalay, J. Trimble, K. Mpofu, R. Muvunzi, A systematic review of process uncertainty in Ti5Al4V-selective laser melting, CIRP Journal of Manufacturing Science and Technology 36 (2022) 185–212.

[8] L. Quezada, E. Reinao, P. Palominos, A. Oddershede, Measuring performance using SWOT analysis and balanced scorecard, Procedia Manuf. 39 (2019) 786–793.

[9] Weinan E., Jianfeng L., Multi-scale modelling, Scholarpedia 1 (2011) Available at: http://www.scholarpedia.org/article/Multi-scale_modelling. (Accessed 20 May 2020).

[10] M. Eriten, Multi-scale Physics-Based Modelling of Friction, University of Illinois, Chicago, IL, 2012. Doctorate Dissertation.

[11] C. Zhen, Y. Xiang, Z. Wei, P. Wei, B. Lu, L. Zhang, J. Du, Thermal dynamic behavior during selective laser melting of K418 superalloy: numerical simulation and experimental verification, Appl. Phys. A 124 (2018) 1–16. March.
[12] T. Rayna, L. Striukova, From rapid prototyping to home fabrication: how 3D printing is changing business model innovation, Technol. Forecast. Soc. Change 102 (2016) 214–224.
[13] S. Chung, A.H.I. Lee, W.L. Pearn, Analytic network process (ANP) approach for product mix planning in semiconductor fabricator, Int. J. Prod. Econ. 96 (2005) 15–36.
[14] T. Saaty, The fundamentals of the analytic network process-dependence and feedback in decision-making with a single network, J. Syst. Sci. Syst. Eng. 13 (2) (2021) 129–157.
[15] İ. Yüksel, M. Dağdeviren, Using the analytic network process (ANP) in a SWOT analysis-A case study for a textile firm, Inf. Sci. 177 (16) (2007) 3364–3382.
[16] T. Mayer, G. Brändle, A. Schönenberger, R. Eberlein, Simulation and validation of residual deformations in additive manufacturing of metal parts, Heliyon 6 (5) (2020) e03987.
[17] A. Li, S. Butler, Forward modelling of magnetotellurics using Comsol Multiphysics, Applied Computing and Geosciences 12 (2021) 100073.
[18] V. Wickramasinghe, S. Takano, Application of combined SWOT and Analytic Hierarchy Process (AHP) for tourism revival strategic marketing planning: a Case of Sri Lanka tourism, Journal of the Eastern Asia Society for Transportation Studies 8 (2010) 954–969.
[19] T. Gatsos, K.A. Elsayed, Y. Zhai, D.A. Lados, Review on computational modelling of process - microstructure -property relationships in metal additive manufacturing, J. Met. 72 (1) (2020) 403–419.
[20] S. Costa, F. Duarte, J. Covas, Thermal conditions affection heat transfer in FDM/FFE: a contribution towards the numerical modelling of the process, Virtual Phys. Prototyp. 10 (1) (2015) 35–46.
[21] Y. Zhang, K. Chou, A Parametric Study of Part Distortions in Fused Deposition Modelling Using Three- Dimensional Finite Element Analysis, Proc. IMechE (Part B), 2008, p. 222.
[22] R. Gabi, J. Seibl, B. Gems, M. Aufleger, 3-D- Numerical Approach to Simulate an Avalanche Impact into a Reservoir, 2015.
[23] F. Liu, Q. Zhang, W. Zhou, J. Zhao, J. Chen, Micro scale 3D FEM simulation on thermal evolution within the porous structure in selective laser sintering, J. Mater. Process. Technol. 212 (10) (2012) 2058–2065.
[24] J. Roopa, H. Swathi, K. Geetha, B. Satyanaryana, Modelling and simulation of triboelectric nanogenerator for energy harvesting using COMSOL Multiphysics® and optimization on thickness of flexible polymer, Mater. Today: Proc. 52 (1) (2021).
[25] C.H. Cheng, K.L. Yang, C.L. Hwang, Evaluating attack helicopters by AHP based on linguistic variable weight, Eur. J. Oper. Res. 116 (2) (1999) 423–435.
[26] J. Ning, M. Praniewicz, W. Wang, J.R. Dobbs, S.Y. Liang, Analytical modelling of part distortion in metal additive manufacturing, Int. J. Adv. Manuf. Technol. 8 (1) (2020) 1–9. Dec.
[27] S. Sadik, A. Yavari, Geometric nonlinear thermos-elasticity and the time evolution of thermal stresses, Math. Mech. Solid 22 (7) (2017) 1546–1587. Dec.
[28] M. Saif, C.Y. Hui, A.T. Zehnder, Interface shear stresses induced by non-uniform heating of a film on a substrate, Thin Solid Films 224 (2) (1993) 159–167. July.
[29] D.L. Mcdowell, An approximate algorithm for elastic-plastic two-dimensional rolling/sliding contact, Wear 211 (2) (1997) 237–246. Sept.
[30] N. Peter, Z. Pitts, S. Thompson, A. Saharan, Benchmarking build simulation software for laser powder bed fusion of metals, Addit. Manuf. 36 (2020) 101531.
[31] Additive works. https://additive.works/, 2021. (Accessed 5 May 2021).
[32] Ansys.com, Ansys | Engineering Simulation Software, 2021 [online] Available at: https://www.ansys.com/. (Accessed 5 May 2021).
[33] COMSOL, COMSOL: Multiphysics Software for Optimizing Designs, 2021 [online] Available at: https://www.comsol.com/. (Accessed 5 May 2021).
[34] ESI Group, ESI Group - Leading Innovator in Virtual Prototyping Solutions [online] Available at:, 2021. esi- group.com/. (Accessed 5 May 2021).
[35] FLOW-3D, FLOW-3D. https://www.flow3d.com/, 2021. (Accessed 5 May 2021).
[36] AlphaSTAR Corporation, AlphaSTAR Corporation, 2021 [online] Available at: https://www.alphastarcorp.com/. (Accessed 5 May 2021).
[37] Autodesk.com, Autodesk Empowers Innovators Everywhere to Make the New Possible, 2021 [online] Available at: https://www.autodesk.com/. (Accessed 5 May 2021).
[38] Mscsoftware.com, MSC software corporation simulating reality, delivering certainty. https://www.mscsoftware.com/, 2021. (Accessed 5 May 2021).
[39] Simuleon, SIMULIA Abaqus Software, Training & FEA Consultancy, 2021 [online] Available at: https://www.simuleon.com/. (Accessed 5 May 2021).
[40] I. Roberts, C. Wang, R. Esterlein, M. Stanford, D. Mynors, A three-dimensional finite element analysis of the temperature field during laser melting of metal powders in additive layer manufacturing, Int. J. Mach. Tool Manufact. 49 (12–13) (2009) 916–923.
[41] R. Li, Y. Shi, J. Liu, H. Yao, W. Zhang, Effects of processing parameters on the temperature field of selective laser melting metal powder, Powder Metall. Met Ceram. 48 (3–4) (2009) 186–195.
[42] D. Zhang, Q. Cai, J. Liu, L. Zhang, R. Li, Select laser melting of W–Ni–Fe powders: simulation and experimental study, Int. J. Adv. Des. Manuf. Technol. 51 (5–8) (2010) 649–658.
[43] M. Zaeh, G. Branner, Investigations on residual stresses and deformations in selective laser melting, J. Inst. Eng. Prod. 4 (1) (2010) 35–45.
[44] N. Contuzzi, S.L. Campanelli, A.D. Ludovico, 3D finite element analysis in the Selective Laser Melting process, Int. J. Simulat. Model. 10 (3) (2011) 113–121.
[45] J. Zhang, D. Li, B. Qiu, L. Zhao, Simulation of temperature field in selective laser sintering on PA6/Cu composite powders, Adv. Mater. Res. 213 (2011) 519–523.
[46] B. Song, S. Dong, H. Liao, C. Coddet, Process parameter selection for selective laser melting of Ti6Al4V based on temperature distribution simulation and experimental sintering, Int. J. Adv. Des. Manuf. Technol. 61 (9–12) (2011) 967–974.
[47] J. Yin, H. Zhu, L. Ke, W. Lei, C. Dai, D. Zuo, Simulation of temperature distribution in single metallic powder layer for laser micro-sintering, Comput. Mater. Sci. 53 (1) (2012) 333–339.
[48] L. Papadakis, G. Branner, A. Schober, K.H. Richter, T. Uihlein, Numerical modelling of heat effects during thermal manufacturing of aero engine components, in: IAENG World Congress on Engineering, IAENG, Hong Kong, 2012.
[49] T. Krol, C. Seidel, J. Schilp, M. Hofmann, W. Gan, M. Zaeh, Verification of structural simulation results of metal-based additive manufacturing by means of neutron diffraction, Phys. Procedia 41 (2013) 849–857.
[50] A. Hussein, L. Hao, C. Yan, R. Everson, Finite element simulation of the temperature and stress fields in single layers built without-support in selective laser melting, Mater. Des. 52 (2013) 638–647.
[51] N. Keller, V. Ploshikhin, New Method for Fast Predictions of Residual Stress and Distortion of Am Parts, 2014.
[52] J. Schilp, C. Seidel, H. Krauss, J. Weirather, Investigations on temperature fields during laser beam melting by melting by means of process monitoring and multi-scale process modelling, Adv. Mech. Eng. 6 (1) (2014) 217584.
[53] Y. Li, D. Gu, Parametric analysis of thermal behavior during selective laser melting additive manufacturing of aluminum alloy powder, Mater. Des. 63 (1) (2014) 856–867.
[54] B. Schoinochoritis, D. Chantzis, K. Salonitis, Simulation of metallic powder bed additive manufacturing processes with the finite element method: a critical review, in: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 231, 2016, pp. 96–117, 1.
[55] S. Afazov, W.A. Denmark, B.L. Toralles, A. Holloway, A. Yaghi, Distortion prediction and compensation in selective laser melting, Addit. Manuf. 17 (1) (2017) 15–22.
[56] D. Jankovics, H. Gohari, A. Barari, Constrained topology optimization for additive manufacturing of structural components in Ansys, Progress in Canadian Mechanical Engineering 1 (2018) 1–6.
[57] J. Ansari, D.S. Nguyen, H.S. Park, Investigation of SLM process in terms of temperature distribution and melting pool size: modelling and experimental approaches, Materials 12 (1) (2019) 1272.
[58] Q. Cheng, X. Liang, D. Hayduke, J. Liu, L. Cheng, J. Oskin, R. Whitmore, A.C. To, An inherent strain based Multi-scale modelling framework for simulating part-scale residual deformation for direct metal laser sintering, Addit. Manuf. 28 (1) (2019) 406–418.

[59] B. Barroqueiro, A. Andrade-Campos, R. Valente, V. Neto, Metal additive manufacturing cycle in aerospace industry: a comprehensive review, Journal of Manufacturing and Materials Processing 3 (3) (2019) 52.
[60] S. Kumar, A. Narayan, Tensile testing and evaluation of 3D printed PLA specimens as per ASTM D638 type-IV standard, Mechanik 90 (7) (2020) 605–607.
[61] X. Song, S. Feih, W. Zhai, C. Sun, F. Li, R. Maiti, J. Wei, Y. Yang, V. Oancea, L. Romano Brandt, A. Korsunsky, Advances in additive manufacturing process simulation: residual stresses and distortion predictions in complex metallic components, Mater. Des. 193 (2020) 108779.
[62] D. Sahini, J. Ghose, S. Jha, A. Behera, A. Mandal, Optimization and simulation of additive manufacturing processes, Advances in Civil and Industrial Engineering (2020) 187–209.
[63] M.D. Nieto, S.D. Moreno, Design for additive manufacturing: tool review and a case study, Appl. Sci. 11 (4) (2021) 1571.
[64] Y. Loginov, A. Koptyug, V. Popov, S. Belikov, G. Mukanov, A. Golodnov, S. Stepanov, Compression deformation and fracture behavior of additively manufactured Ti–6Al–4V cellular structures, International Journal of Lightweight Materials and Manufacture 5 (1) (2022) 126–135.
[65] A. Chandorkar, S. Palit, Simulation of droplet dynamics and mixing in microfluidic devices using a VOF- based method, Sensors & Transducers Journal 1 (1) (2009) 1–13.
[66] A. ArkanIbrahimi, A. Karim, M. Günal, Simulation and study of sediment transport and scouring downstream of perforated hump step broad crested weirs, European Journal of Science and Technology 5 (1) (2016) 13.
[67] S. Dawoodjasim, A. Yuce, Assessment flow 3d program efficiency comparing with laboratory models, Int. J. Adv. Res. 4 (12) (2016) 1691–1696.
[68] A.I. Rajaa, A.H. Kamel, Performance study of fluent-2D and flow-3D platforms in the CFD modelling of a flow pattern over ogee spillway, Anbar Journal of Engineering Science 1 (1) (2020) 317–328.
[69] J.P. Kruth, J. Deckers, E. Yasa, R. Wauthle, Assessing and comparing influencing factors of residual stresses in selective laser melting using a novel analysis method, Proc IMechE Part B: J. Engineering Manufacture 1 (1) (2012) 1–12.
[70] V. Gerlich, K. Sulovská, M. Zálešák, COMSOL Multiphysics validation as simulation software for heat transfer calculation in buildings: building simulation software validation, Measurement 46 (6) (2013) 2003–2012.
[71] E. Lacatus, G. Alecu, A. Tudor, Simulation of Dynamic Thermal Fields Assisting DMLS Additive Manufacturing of Biocompatible Ti-Alloy, Polytechnic University of Bucharest, Grenoble, 2015, pp. 1–15.
[72] K. Chang, Rapid Prototyping, e-Design, 2015, pp. 743–786.
[73] H. Bikas, P. Stavropoulos, G. Chryssolouris, Additive manufacturing methods and modelling approaches: a critical review, Int. J. Adv. Manuf. Technol. 83 (1–4) (2016) 389–405.
[74] A. Anagnostopoulos, A. Campbell, H. Arellano-Garcia, Modelling of the Thermal Performance of SGSP Using COMSOL Multiphysics, Computer Aided Chemical Engineering, 2017, pp. 2575–2580.
[75] A. Ngoveni, A. Popoola, N. Arthur, S. Pityana, Residual stress modelling and experimental analyses of Ti6Al4V ELI additive manufactured by laser engineered net shaping, Procedia Manuf. (35) (2019) 1001–1006.
[76] J. Zhang, X. Li, D. Xu, R. Yang, Recent progress in the simulation of microstructure evolution in titanium alloys, Prog. Nat. Sci.: Mater. Int. 29 (3) (2019) 295–304.
[77] B. Basu, A. Lundback, L.E. Lindgren, Simulation of Ti-6Al-4V Additive manufacturing using coupled physically based flow stress and metallurgical model, Materials 12 (23) (2019) 12233844.
[78] W. Wijayanti, Musyaroh, M. Sasongko, R. Kusumastuti, Sasmoko, Modelling analysis of pyrolysis process with thermal effects by using Comsol Multiphysics, Case Stud. Therm. Eng. 28 (2021) 101625.
[79] V. Kostin, G. Grigorenko, Simulation of the Additive Process of Forming 3D Products from HSLA Steel 09G2S, E. O. Paton Electric Welding Institute of the NAS of Ukarine, Rotterdam, 2021, pp. 1–13.
[80] P. Mercelis, J.P. Kruth, Residual stresses in selective laser sintering and selective laser melting, Rapid Prototyp. J. 12 (5) (2006) 254–265.
[81] D. Türk, L. Triebe, M. Meboldt, Combining additive manufacturing with advanced composites for highly integrated robotic structures, Procedia CIRP 50 (2016) 402–407.
[82] S. Talagani, R. DorMohammadi, C. Dutton, E. Godines, Numerical simulation of big area additive manufacturing (3D printing) of a full-size car. Feature article, SAMPE J. 51 (4) (2016) 1–10.
[83] X. Song, Residual Stress Modelling and Measurement of Material Addition Thin Wall Buildups, Rolls Royce Industry Report, Singapore Institute of Manufacturing Technology, AlphaStar, 2017.
[84] D. Brackett, I. Ashcroft, R. Hague, Topology optimization for additive manufacturing. https://sffsymposium.engr.utexas.edu/Manuscripts/2011/2011- 27-Brackett, 2011. (Accessed 25 June 2020).
[85] K. Neugebauer, X. Ploshikhin, Thermo-mechanical Simulation of Additive Layer Manufacturing of Titanium Aerospace Structures Proceedings of Light anisMAT, 2013.
[86] K. Neugebauer, X. Ploshikhin, F. Koehler, Multi Scale FEM Simulation for Distortion Calculation in Additive Manufacturing of Hardening Stainless-Steel Proceedings of International Workshop on Thermal Forming and Welding Distortion, 2014.
[87] I. Ferguson, M. Frecker, T.W. Simpson, C.J. Dickman, Topology optimization software for additive manufacturing: a review of current capabilities and a real-world example, in: Volume 2A: 42nd Design Automation Conference, ASME: Charlotte, NC, USA, 2016.
[88] E. Gouge, K. Michaleris, Thermo-Mechanical Modelling of Additive Manufacturing, first ed., Butterworth-Heinemann, Oxford, 2017.
[89] A. Borovkov, L. Maslov, K. Ivanov, E. Kovaleva, F. Tarasenko, M. Zhmaylo, Improving the printing process stability and the geometrical accuracy of the parts manufactured by the additive techniques, IOP Conf. Ser. Mater. Sci. Eng. 986 (1) (2020) 012033.
[90] C.S. Elisel, Evaluation of design support tools for additive manufacturing and conceptualisation of an integrated knowledge management framework, in: DS 111: Proceedings of the 32nd Symposium Design for X, vol. 10, 2021 35199. Available at: https://www.designsociety.org/publication/43577/Evaluation+of+design+support+tools+for+additive+manufacturing+and+conceptualisation+of+an+integrated+knowledge+management+framework. (Accessed 20 September 2020).
[91] V. Stiuso, P. Minetola, F. Calignano, M. Galati, M. Khandpur, L. Fontana, Experimental assessment of compensated distortion in selective laser melting of Ti6Al4V parts, IOP Conf. Ser. Mater. Sci. Eng. 1136 (1) (2021) 012048.
[92] W. Jianhua, Application of Simufact software in plastic machining, Aviation Precision Manufacturing Technology 2 (2010) 43.
[93] F. Neugebauer, N. Keller, X. Hongxiao, Simulation of Selective Laser Melting Process Using Specific Layer-Based Meshing, Fraunhofer Verlag, Berlin, Stuttgart, 2014.
[94] I.H. Hwang, P. Mehmet, M. Tran, Metal additive manufacturing process simulation for the hinge of the engine hood, Koreana: Kore Hassas Mühendislik, Derneği 1 (1) (2017).
[95] A. Wiberg, J. Persson, J. Ölvander, An optimization framework for additive manufacturing given topology optimization results, in: Twelfth International Symposium on Tools and Methods of Competitive Engineering. Las Palmas de Gran Canaria, TMCE, Spain, 2018, 2018.
[96] A. Çelebi, E. Appavuravther, Analyzing the Effect of Voxel-Based Surface Mesh Application on Residual Stress with Simufact Additive Software, vol. 6, Düzce University Journal of Science & Technology, 2018, pp. 930–940.
[97] F. Mezzadri, V. Bouriakov, X. Qian, Topology optimization of self-supporting support structures for additive manufacturing, Addit. Manuf. 21 (2018) 666–682.
[98] M.S. Sebastian, I. Setien, A.M. Mancisidor, A. Echeverria, SLM (Near)-Net-Shape Part Design optimization based on numerical prediction of process induced distortions, Addit. Manuf. 23 (2018) 117–126.
[99] C. Seidel, M.F. Zaeh, Multi-scale modelling approach for contributing to reduced distortion in parts made by laser-based powder bed fusion, Procedia CIRP 67 (2018) 197–202.
[100] X. Liang, L. Cheng, Q. Chen, Q. Yang, A.C. To, A modified method for estimating inherent strains from detailed process simulation for fast residual distortion prediction of single-walled structures fabricated by directed energy deposition, Addit. Manuf. 23 (2018) 471–486.

[101] A. Wiberg, J. Persson, J. Ölvander, Design for additive manufacturing – a review of available design methods and software, Rapid Prototyp. J. 6 (25) (2019) 1080–1094.
[102] H. Chang, Numerical Simulation of Forming Stress and Deformation of GH4169 Powder SLM Based on Simulact, Shandong Jianzhu University, 2019.
[103] G. Allaire, M. Bihr, B. Bogosel, Support optimization in additive manufacturing for geometric and thermo-mechanical constraints, Struct. Multidiscip. Optim. 61 (6) (2020) 2377–2399.
[104] M. Pagac, J. Hajnys, R. Halama, T. Aldabash, J. Mesicek, L. Jancar, J. Jansa, Prediction of model distortion by FEM in 3D printing via the selective laser melting of stainless steel AISI 316L, Appl. Sci. 11 (4) (2021) 1656.
[105] T. Taufek, Y. Manurung, S. Lüder, M. Graf, F. Salleh, Distortion analysis of SLM product of SS316L using inherent strain method, IOP Conf. Ser. Mater. Sci. Eng. 834 (1) (2020) 012011.
[106] L. Zhao, H. Gu, J. Xu, Y. Cui, C. Shuai, Research on Simufact simulation data processing system based on QT and MySQL, Applied Mathematics and Nonlinear Sciences 6 (2) (2021) 423–433.
[107] X.C. Wang, J.P. Kruth, A Simulation Model for Direct Selective Laser Sintering of Metal Powders, Computational Techniques for Materials, Composites and Composite Structures, Civil-Comp press, Edinburgh, 2000.
[108] S. Kolossov, E. Boillat, R. Glardon, P. Fischer, M. Locher, 3D FE simulation for temperature evolution in the selective laser sintering process, Int. J. Mach. Tool Manufact. 44 (2–3) (2004) 117–123.
[109] T. Chen, Y. Zhang, Numerical simulation of two- dimensional melting and re-solidification of a two-component metal powder layer in selective laser sintering process, Numer. Heat Tran., Part A: Applications 46 (7) (2010) 633–649. Liu.
[110] N. Shen, K. Chou, Thermal modelling of electron beam additive manufacturing process-powder sintering effects, in: Proceeding the 7th AMSE International Manufacturing Science and Engineering Conference, 2012, pp. 287–295.
[111] N. Shen, K. Chou, Numerical Thermal Analysis in Electron Beam Additive Manufacturing with Preheating Effects, 23rd Solid Freeform Fabrication Symposium, 2012, pp. 774–784.
[112] Z. Shiqing, W. Peng, F. Zhenhua, S. Jiguo, Numerical simulation of wire temperature field for prediction of wire transfer stability in laser hot wire welding, in: Proceedings of the 32nd Congress on Applications of Lasers & Electro-Optics, vol. 294, ICALEO, Miami, 2013, pp. 294–301.
[113] V. Stiuso, P. Minetola, F. Calignano, M. Galati, Khandpur, G. Strano, L. Hao, R.M. Everson, K.E. Evans, A new approach to the design and optimisation of support structures in additive manufacturing, Int. J. Adv. Des. Manuf. Technol. 66 (9–12) (2013) 1247–1254.
[114] G. Strano, L. Hao, R.M. Everson, K.E. Evans, Surface roughness analysis, modelling and prediction in selective laser melting, J. Mater. Process. Technol. 213 (4) (2013) 589–597.
[115] Y. Kanada, 3D-printing of generative art by using combination and deformation of direction-specified 3D parts, in: 4th International Conference on Additive Manufacturing and Bio-Manufacturing, ICAM-BM, Beijing, 2014.
[116] Y. Kanada, Method of designing, partitioning, and printing 3D objects with specified printing direction, in: International Symposium on Flexible Automation, ISFA, Beijing, 2014.
[117] Y. Kanada, 3D-Printing plates without "support", International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering 9 (5) (2015) 1–7.
[118] B. Ahuja, M. Karg, M. Schmidt. Additive manufacturing in production: challenges and opportunities, Laser 3D Manufacturing II, 2015, p. 9353.
[119] F.R. Liu, Q. Zhang, W.P. Zhou, J.J. Zhao, J.M. Chen, Micro scale 3D FEM simulation on thermal evolution within the porous structure in selective laser sintering, J. Mater. Process. Technol. 212 (10) (2015) 2058–2206.
[120] M.F. Gouge, J.C. Heigel, P. Michaleris, T.A. Palmer, Modelling forced convection in the thermal simulation of laser cladding processes, Int. J. Adv. Manuf. Technol. 79 (2015) 307–320.
[121] G. Belgiu, C. Cărăuşu, D. Şerban, C. Turc, Product management of making large pieces through Rapid Prototyping PolyJet® technology, IOP Conf. Ser. Mater. Sci. Eng. 227 (2017) 012015.
[122] Z. Nie, G. Wang, J.D. McGuffin-Cawley, B. Narayanan, S. Zhang, D. Schwam, M. Kottman, Y. Rong, Experimental study and modelling of H13 steel deposition using laser hot-wire additive manufacturing, J. Mater. Process. Technol. 235 (2016) 171–186.
[123] M.P.N. Bui, S. Ahmed, A. Abbas, Finite element modelling of selective laser melting, Addit. Manuf. 77 (2019) 249–263.
[124] H. Taylor, E. Garibay, R. Wicker, Toward a common laser powder bed fusion qualification test artifact, Addit. Manuf. 39 (2021) 101803.
[125] G. Hatala, Q. Wang, E. Reutzel, C. Fisher, J. Semple, A thermo-mechanical analysis of laser hot wire additive manufacturing of NAB, Metals 11 (7) (2021) 1023.
[126] W. Jiang, K.W. Dalgarno, T.H.C. Childs, Finite element analysis of residual stresses and deformations in direct metal SLS process, in: National Science Foundation Solid Freeform Fabrication Symposium, Laboratory for Freeform Fabrication, Austin, TX, 2002.
[127] Y. Zhang, Y.K. Chou, 3D FEA simulations of fused deposition modelling process, in: International Conference on Manufacturing Science and Engineering, ASME, Ypsilanti, MI, 2006.
[128] L. Van Belle, G. Vansteenkiste, J.C. Boyer, Comparisons of numerical modelling of the selective laser melting, Key Eng. Mater. 504 (506) (2012), 1067–10.
[129] T. Mukherjee, A. De, Three-dimensional heat transfer analysis of laser selective melting process, Indian Weld. J. 47 (4) (2014) 57.
[130] X. Song, M. Xie, F. Hofmann, T. Illston, T. Connolley, C. Reinhard, R.C. Atwood, L. Connor, M. Drakopoulos, L. Frampton, A.M. Korsunsky, Residual stresses and microstructure in powder bed direct laser deposition (PB DLD) samples, Int. J. Material Form. 8 (2) (2015) 245–254.
[131] M.R. Talagani, S. DorMohammadi, R. Dutton, C. Godines, H. Baid, F. Abdi, V. Kunc, B. Compton, S. Simunovic, C. Duty, L. Love, B. Post, C. Blue, Numerical simulation of big area additive manufacturing (3D printing) of a full-size car, SAMPE J. 51 (4) (2015) 27–36.
[132] L. Parry, I.A. Ashcroft, R.D. Wildman, Understanding the effect of laser scan strategy on residual stress in selective laser melting through thermo - mechanical simulation, Addit. Manuf. 12 (A) (2016) 1–15.
[133] A.J. Dunbar, E.R. Denliger, M.F. Gouge, P. Michaleris, Experimental validation of finite element methodology for laser powder bed fusion deformation, Addit. Manuf. 12 (2016) 108–120.
[134] T. Mukherjee, W. Zhang, T. DebRoy, An improved prediction of residual stresses and distortion in additive manufacturing, Comput. Mater. Sci. 126 (2017) 360–372.
[135] Y. Yang, M. Allen, T. London, V. Oancea, Residual strain predictions for a powder bed fusion Inconel 625 single cantilever part, Integrating Materials and Manufacturing Innovation 8 (2019) 294–304.
[136] L. Bertini, F. Bucchi, F. Frendo, M. Moda, D. Monelli, Residual stress prediction in selective laser melting, Int. J. Adv. Des. Manuf. Technol. 105 (2019) 609–636.
[137] A.J. Favaloro, B. Brenken, E. Barocio, R.B. Pipes, Simulation of polymeric composites additive manufacturing using abaqus. West lafayette, in: School of Aeronautics and Astronautics, Purdue University, 2019.