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PROJECT FINAL REPORT

Grant Agreement number: 287087

Project acronym: AEROSIM

Project title: Development of Selective Laser melting (SLM) Simulation tool for Aero Engine applications

Funding Scheme: JTI-CS

Period covered: **from** 05/2012 **to** 08/2015

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Final publishable summary report

Executive Summary

Laser Beam Melting is an additive manufacturing (AM, often referred to as "3D-printing") process that allows the production of full dense metal parts. The build-up is done layer by layer enabling the production of almost arbitrarily complex geometries. Therefore, Laser Beam Melting exhibits a significant advantage compared to conventional machining where manufacturing costs typically increase with the part's geometrical complexity. As a result, experts expect the market for systems, services and materials for AM to quadruple in the next 10 years. The simulation tool developed within the research project AeroSim strives to contribute to improve the Technology Readiness Level (TRL, [1]) of Additive Manufacturing and particularly Laser Beam Melting.

Metal-based additive manufacturing processes can be used for the environment-friendly production of light weight aero engine components. However, high standards concerning the process stability and the resulting part quality need to be fulfilled. Today, the part specific process of identifying a set of process parameters and design, which lead to the fulfilment of the given quality standard, is often conducted by manufacturing test samples. Thereby, different objective criteria (e. g. minimized distortions) should be improved by means of adjusting the process parameter configuration. These experiments are not enhancing the final product value but lead to a higher material usage, a high staff allocation and a decreased system availability. In May 2012, the Institute for Machine Tools and Industrial Management (iwb) of the Technische Universitaet Muenchen and the MTU Aero Engines AG started AeroSim with the aim of developing a simulation tool for Aero Engine applications. The main objective of the research project is the development of a numerical model that is able to predict resulting part properties with a high accuracy in order to replace the manufacturing of samples and to allow for a virtual quality control. By modelling material properties, process parameters and ambient influences, the prediction of temperature fields, residual stress and distortion occurring in the produced part is possible. To achieve a high performance level of the simulation system (sufficient result accuracy within shortest possible calculation time) suitable abstraction methods are developed. For example, efficient meshing algorithms for mapping complex part geometries as well as abstractions concerning the heat input have been investigated. In addition, the desired software tool contains an optimization-algorithm and a GUI, which provides intuitively understandable visualization of the simulation results and can be used without profound expertise in simulation and programming.

On the microscale level, process phenomena (e. g. melt pool dynamics) can be investigated by utilizing the process model. For analyzing resulting residual stress states or distortions of built parts, a macroscale model of the build process was developed. The validity of abstractions on the macroscale are derived from investigations on the microscale by utilizing the process model. To guarantee maximum user benefit, suitable interfaces, also with the additive manufacturing machine, were developed. Furthermore, the simulation models are connected to a user-friendly optimization system. The considered materials within AeroSim are nickel-base super alloy Inconel 718 and titanium-base alloy Ti-6Al-4V.

Summary description of project contents and objectives

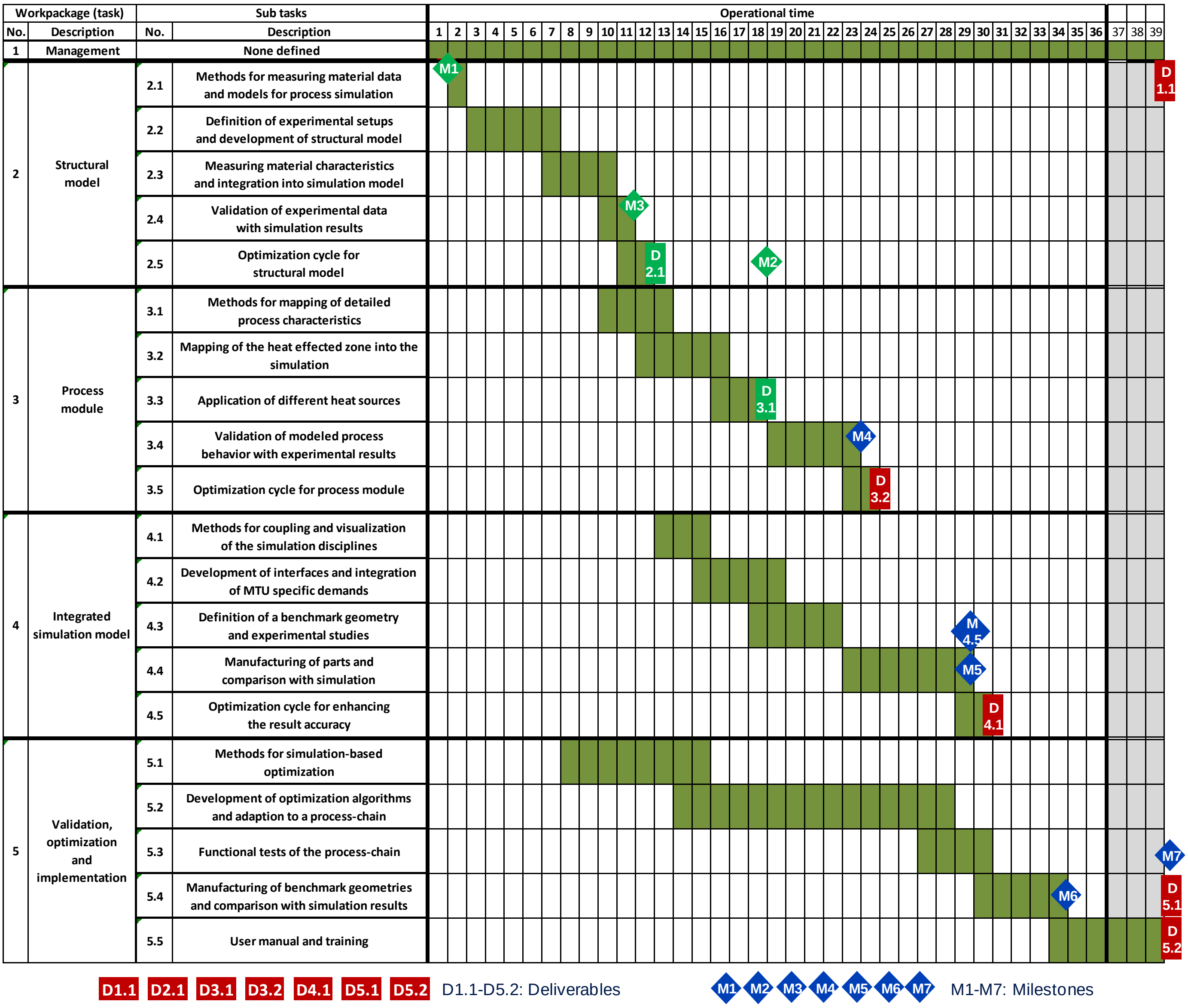

Figure 1: Project plan under consideration of a 3 month project extension (cf. Amendment No.1)

The main objective of the first project year was to develop a structural model (work package (WP) 2) for the simulation of the laser melting process, as specified in deliverable 2.1. The core of the structural model is a simulation framework which exhibits the possibility to predict temperature fields, residual stresses and distortions in the additively manufactured part. Besides the development of the structural model, methods concerning the mapping of detailed process characteristics were investigated (WP 3.1) and the heat affected zone was modelled (WP 3.2). Moreover, methods for a simulation based optimization and for a simulation diagnosis were investigated (WP 5.1).

The project consortium decided to focus on model development within project year 1 and 2 (WP 2, 3 and 4) in order to ensure the best possible integrated model to be implemented in an optimization system (WP 5). This comprises for example the increase of the degree of automation of the implemented model based on the structural model (e. g. realized through interfaces) and the development of methods for coupling and visualization of the simulation disciplines. Furthermore, the attempt to consider and explicitly implement the physical effect of evaporation within the process module in order to enhance accuracy in temperature regions above the melting point failed due to a lack of model stability and calculation time. However, the result accuracy of the process module could be significantly increased by utilizing the Finite-Volume-Method that allows for considering fluid dynamic effects within the melt pool. This was found to be relevant to ensure the best possible quality of the calibrated heat source of the integrated simulation model (WP 4).

The main objective within project year 3 was to ensure a systematic, thorough transfer of the developed simulation system to the MTU Aero Engines AG IT infrastructure and more importantly pinpointing the benefit for the later users. The machine-data-based process chain was found to be robust and highly automatable, but the respective results can only be used in a qualitative fashion due to the distinct staircase effect introduced by the straight extrusion of meshed areas. With the high calculation times, a reduction of the height of the layer compounds was not deemed practical to compensate for this effect. Accordingly, a new process chain was developed, in which the mesh is in high agreement with the geometry. This is achieved by slicing the solid model and subsequent meshing of these volumes, yielding a mesh with nodes respecting the joint faces created by the slicing process. The optimization of the simulation process (WP 5) was carried out by introducing an iteratively designed pre-deformation process according to the typical process of raising dimensional accuracy by test manufacturing.

Figure 2 gives an overview over the relevant components and main objectives of the desired tool.

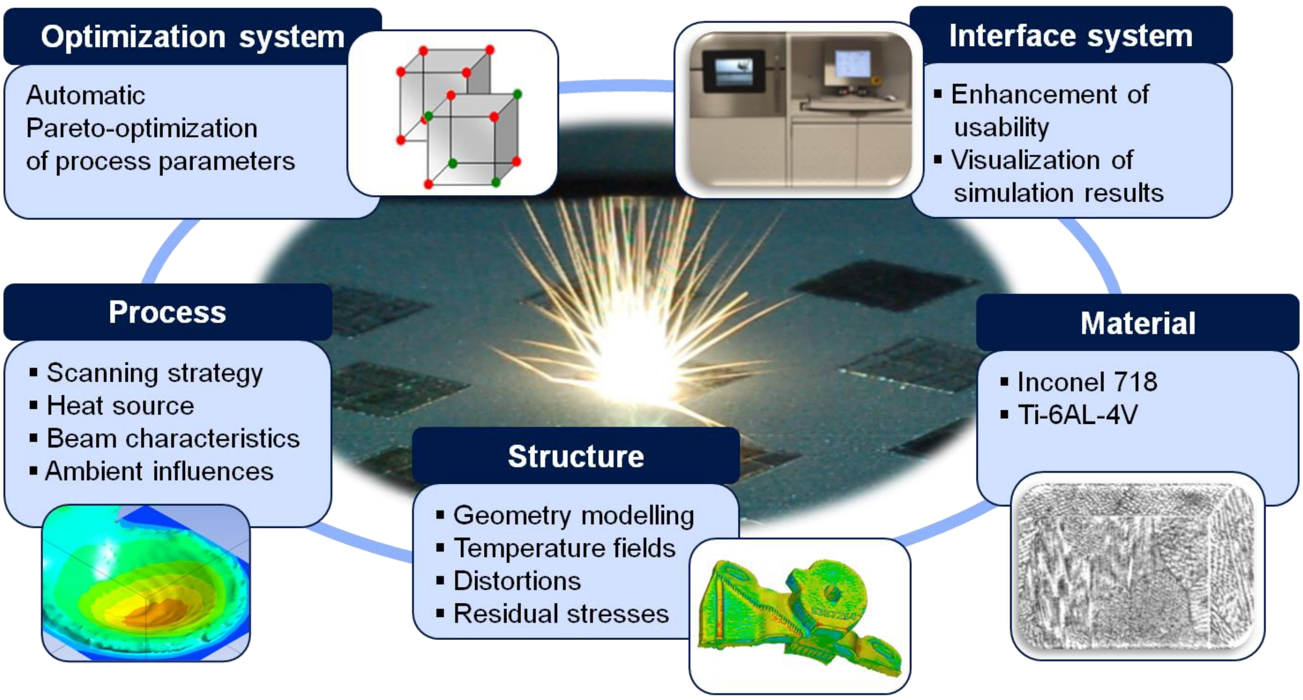

Figure 2: Research project AeroSim – relevant components of the desired simulation tool

Description of the main S&T results/foregrounds

Significant results of project year 1

Measuring techniques for Inconel and Titanium alloys were investigated and suitable measuring equipment was identified (e. g. Gleeble® system for hot tensile tests). The measurements of thermo-mechanical and thermo-physical material data (Inconel 718, Ti6Al4V) were performed (using additively manufactured specimens). Subsequently, the identified material properties were implemented in the simulation model in the form of suitable material models for both Inconel 718 and Ti6Al4V.

Different heat generation methods (e. g. temperature and heat flux based) for the simulation tool were investigated and developed further. The time-dependent temperature profiles during the laser beam melting process were measured by utilizing thermocouples and the heat affected zone was investigated by analyzing etched microsections. Investigations on the detailed mapping of the beam-material-interaction were performed. The obtained results are of use for further research activities.

Additionally, methods for increasing the computing efficiency and the accuracy of the simulation tool were ivnestigated. For instance, mesh generation was further developed and suitable methods for the abstracted mapping of the laser exposure strategy were investigated and applied. Furthermore, a sensitivity analysis (showing the influences of different material properties and the part geometry on the result accuracy) was performed.

Finally, approaches for a simulation diagnosis tool were developed. The simulation diagnosis can support users regarding the application of the simulation software.

Significant results of project year 2

The main objective of the second project year was to develop both the structural and the process module further in order to ensure that the best possible models are implemented in the optimization cycle and the development of the integrated model in project year 3. At this point, complex geometries can be modelled by applying the AeroSim-modelling approach based on machine data (layer and exposure information obtained from the preparation software for Selective Laser Melting).

Moreover, the heat input can be modelled with a varying level of detail and both under consideration of machine data and as a stand-alone-modelling approach. The process environment (e. g. build plate dimensions) can be considered because an efficient way of modeling the build plate was developed. Furthermore, the ANSYS® graphical user interface (GUI) was customized and several diagnosis functions were implemented to enhance the usability of the tool.

Significant results of project year 3

A second, CAD-based process chain was developed in addition to the robust machine-data (CLI) based approach to improve dimensional accuracy of the results, thus increasing the usefulness of the simulated distortions. Additionally, an optimization system was developed to realize an iterative pre-deformation process. Both process chains were adjusted so that they require minimal user interaction. They were tested extensively. The basic concepts of the model as well as the necessary knowledge to work with the developed simulation tool were taught in five training sessions at MTU Aero Engines AG facilities and documented in the corresponding training records. In summary, all milestones and deliverables were reached on time. To ensure the progress of the project (WP 1), regular meetings were held at MTU Aero Engines in Munich.

WP 2: Structural model

Suitable methods for measuring material data were determined within WP 2.1, followed by the experimental design in WP 2.2. The measurements of the material data and their import into the simulation system were objectives of WP 2.3. The focus was on the nickel-base alloy Inconel718. However, the laser beam melting of the titanium-alloy Ti6Al4V was also modelled. Besides investigations concerning the material behavior, models for a process simulation were investigated and a structural model was developed (WP 2.2 and 2.3). In WP 2.4 the structural model was validated by comparing simulation data with experimental results. Simultaneously, the simulation model was optimized within WP 2.5.

Objectives of WP 2 as submitted in Annex I to the GA

- *For the work within this work package as well as for further research tasks, material data should be established. The material data used in this project (nickel-base alloy and titanium) should be summarized and have to be provided for the structural simulation.*
- *To get a better process understanding as well as to map the beam-material-interactions and further process boundary conditions with the simulation, different investigations are executed during this work package. The objective is to map those effects with the simulation.*
- *The project results should be summarized in a structural simulation model and they are the starting point for further detail levels for analyzing the process with the finite element analysis (cp. WP 3).*

WP 2.1 Methods for measuring material data and models for the process simulation

Methods for measuring material data

To predict residual stresses and deformations of additively manufactured parts, the mapping of the material properties is of essential importance.

As a result of the investigation of available measuring systems for analyzing the mechanical behavior, a Gleeble®-system as illustrated in Figure 3 was utilized for the experiments, due to its ability to perform tensile tests at high temperatures (even above the melting point of Inconel718 and Ti6Al4V) and with high strain rates. The latter is important for a testing close to the layered manufacturing, as high strain rates occur during the process due to high temperature gradients.

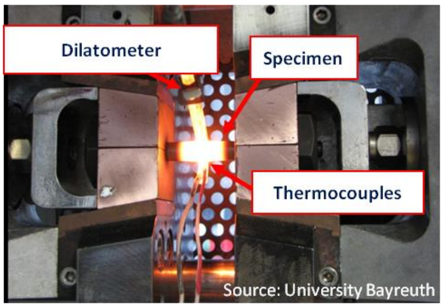

Figure 3: Gleeble®-system for hot tensile tests at the University of Bayreuth. Measurements with this system can provide necessary thermo-mechanical data for the simulation model.

Methods for the integration of scanning strategies

Within this research activity different methods for the modelling of scanning strategies were investigated. The scan vectors were read from CLI-files (containing the layer information and including the exposure strategy) and were imported into the simulation software.

Due to the fact that the detailed mapping of every single melt track would result in unacceptable computation times, approaches for the abstraction of the exposure were investigated. One possible solution is the combination of neighboring scan vectors to an area that is exposed within one solution step.

Approaches for mapping the material behavior

The material behavior can be modelled for the FE structural analysis by the so-called bilinear kinematic hardening model (BKIN), whereby the measured stress-strain-curve is approximated by two straight lines. Therefore, this procedure leads to significant deviations in the mapping of the stress-strain curve, cf. Figure 4. Moreover, the elastic limit and $R_{p0.2}$ are assumed to be equal in this context.

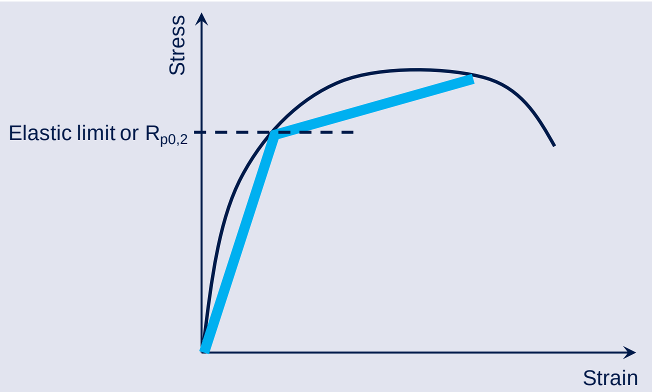

Figure 4: Modelling of stress-strain curves by utilizing the ANSYS® BKIN model (light blue). Elastic limit and $R_{p0.2}$ are assumed to be equal.

Multi-linear material models (approximation of the stress-strain-curve by more than two straight-lines) show a more realistic mapping of the material behavior and were thus implemented in a later phase of the project.

Furthermore, it is known from experience that additively manufactured parts exhibit lower tensile strength parallel to the build direction compared to the tensile strength perpendicular to the build direction (e. g. [2]). Hence, the influence of the process-related anisotropy of the material data was also investigated within this research project.

WP 2.2 Definition of the experimental setups and development of the structural model

Measurement of process temperatures

The objective of this experiment was the determination of time-dependent temperature profiles during the laser beam melting process. As described above, thermocouples were used for this purpose. The experiment was carried out in two stages. Firstly, a pilot test was performed to provide the proof of concept and to obtain necessary transfer functions for the temperature signal. Secondly, the main experiment was designed for measuring the temperature profile as a function of time during the manufacturing process. The transfer functions derived from the pilot test were used to calculate the real temperatures based on the measured signal. The gathered data is of value for the validation of the simulation model.

Measurement of beam profile and caustic

Due to the fact that experimental results (beam profile, caustic) for the optical system of the manufacturing system EOS M270 (optics are identical to EOS M280, which is utilized by the MTU Aero Engines AG) could be provided by the *iwb*, no further measurements were performed within AeroSim. The beam profile in the focal point of the laser is shown in Figure 5. In order to avoid damage to or destruction of the measuring instrument, all measurements were performed with significantly reduced laser power compared to the real manufacturing process. The beam radius (86%-radius) obtained by the experiments was 34 µm in the beam focus. This value is important for the detailed mapping of the heat input in the simulation of a single melt track (WP 3).

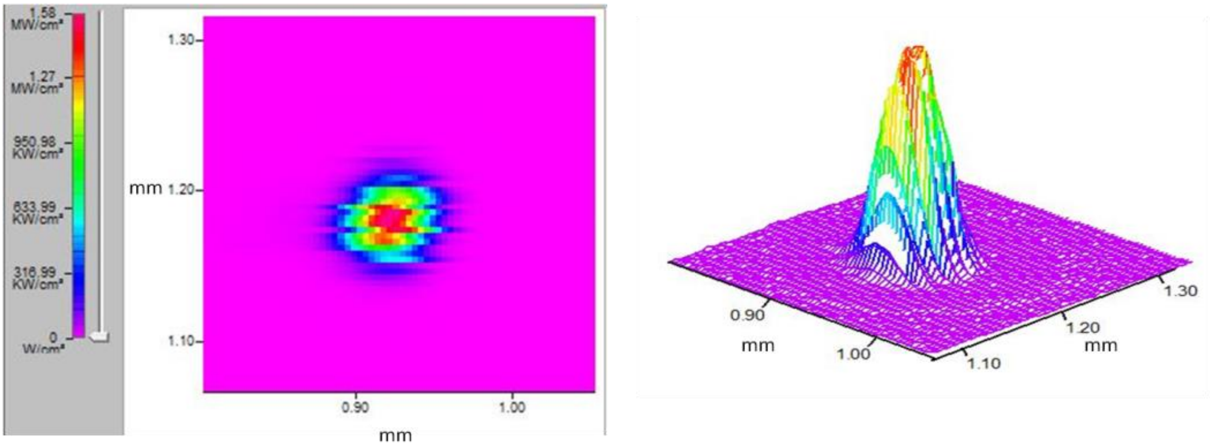

Figure 5*:* Intensity distribution of the laser in the focal point (source: iwb). The beam radius (86%-radius) of the investigated optical system is about 34 µm.

Structural model - Mapping of different part geometries

For the simulation of the layer-wise additive manufacturing process, it is necessary that all nodes representing a single layer or a layer compound are located on the same height. This condition has to be fulfilled at least for the respective topmost layer, where the heat generation takes place. The standard ANSYS® meshing algorithms for tetrahedral or prism elements are not designed to generate meshes with nodes at the same height. Although the usage of hexahedral cubic elements fulfils the mentioned requirement, this approach can result in erroneous or relatively coarse mapping of e. g. filigree structures or free formed surfaces due to the stepped contour modelling. As a consequence, customized mesh generation methods were developed. First, the specimen geometry is imported as a volume body to ANSYS® via the file format *.igs. Within the simulation tool it is sliced into separate volume bodies, followed by the mesh generation using tetrahedral elements (Figure 6). By applying this procedure, the desired nodal positions are achieved and free formed surfaces are mapped simultaneously with increased accuracy compared to cube-based mesh generation algorithms. This process chain was the first try to realize a mesh close to the geometry of the original part. Unfortunately, for more complex parts, the slicing procedure within ANSYS® failed frequently. This was resolved by introducing a CAD-based data chain using Siemens NX® Software for the slicing process, exhibiting a more stable slicing process, i. e. it was more reliable for Boolean operations.

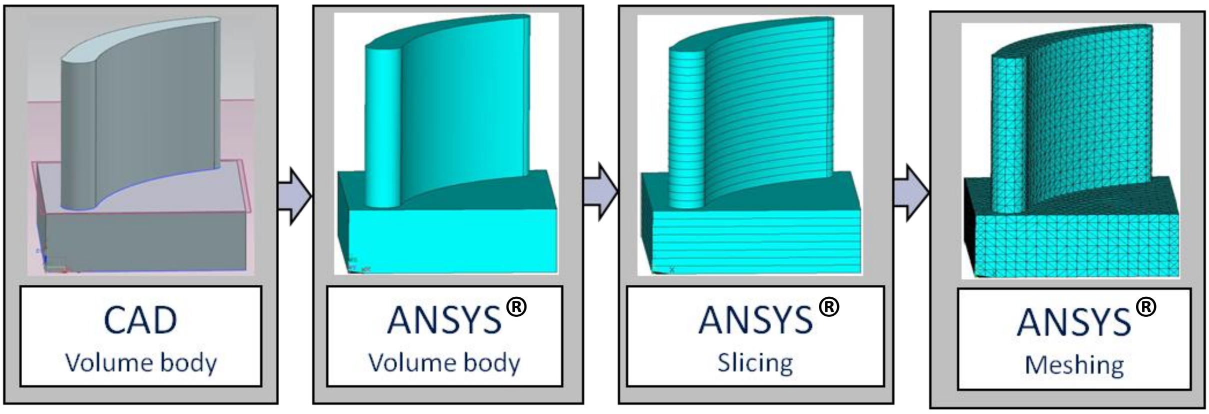

Figure 6: The volume body is imported from the CAD-software to the simulation environment (ANSYS®). Subsequently, the volume body is sliced to several volume bodies representing a layer compound. In the next step, the mesh is generated. As a result, the nodes of one layer compound are located on the same height, which is of importance for the mapping of the heat input.

Structural model - Heat source models

At this point, there are two different methods for mapping the heat input caused by the laser. While one approach prescribes the temperature of nodes within elements of a layer compound, the other one is based on inducing heat energy in terms of a volumetric heat flux density. These approaches have in common that the heat input is modelled by a volumetric heat source.

WP 2.3 Measuring material characteristics and integration into simulation model

Measuring of thermo-physical and thermo-mechanical material data

Several experiments to determine necessary material data were performed. Table 1 gives an overview of measurements for the Inconel718 specimens and Table 2 shows the respective experiments for the titanium alloy.

Table 1: Experiments for Inconel718. Build direction and part orientation refer to the angle between the part's z-axis and the build plate.

Category	Specifications
Thermo-mechanical data In718	▪ 90° build direction ▪ Temperatures: room temperature (RT), 350 °C, 650 °C, 850 °C, 1000 °C ▪ strain rate dependency ▪ anisotropic material behavior ▪ 0°, 45°, 70° part orientation ▪ Temperatures: RT, 350 °C, 650 °C, 850 °C, 1000 °C
Ultrasound resonance In718	0°, 45°, 90° part orientation
Creep In718	▪ T = 200 °C, t=336 h, 600 N/mm2 (no creep observable after 336 hours) ▪ T = 700 °C, t=336 h, 490 N/mm2

Table 2: Experiments for Ti6Al4V. Build direction and part orientation refer to the angle between the part's z-axis and the build plate.

Category	Specifications
Ultrasound resonance Ti6Al4V	0°, 90° build direction
Thermo-mechanical data Ti6Al4V	▪ 90° part orientation ▪ Temperatures: RT, 400°C, 700°C, 1000°C, 1250°C
Thermo-physical data Ti6Al4V	Heat capacity, thermal expansion, thermal conductivity, density

WP 2.4 Validation of the simulation results with experimental data

Validation of the structural model with a specimen – Cantilever (Inconel718)

The structural model has been validated multiple times, for example with a cantilever sample. The cantilever consists of a centered block and two horizontal "wings". Since those wings are parallel to the base plate and have downwards directed surfaces, they had to be manufactured using support structures. In this case, a block support (three-dimensional cubic lattice) was chosen. These support structures were mapped by two-dimensional so-called shell elements [3].

The distortions are compared to experimental results for validating the simulation approaches. The displaced cantilever after the removal of the support is shown in Figure 7.

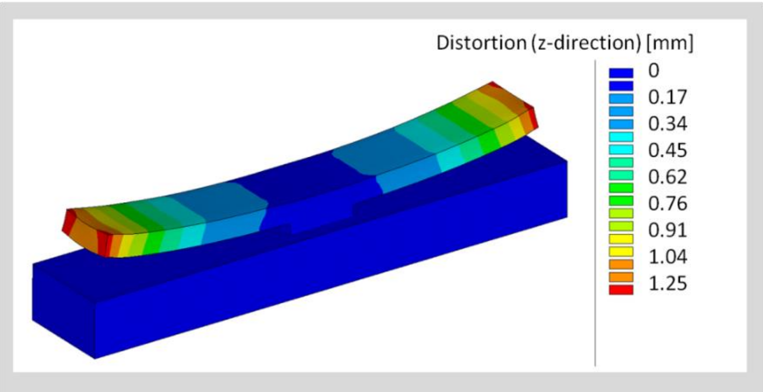

Figure 7: Distortion in z-direction (direction in which the part is built up). The simulation yields a maximum deformation of about 1.25 mm. The measured value is 0.6 mm. Hence, the deviation between simulation and experiment is 0.65 mm.

The simulation yields a maximum distortion in z-direction of 1.25 mm. According to measurements performed by the MTU Aero Engines AG the additively manufactured part exhibits a maximum deformation in z-direction of about 0.6 mm, leaving a factor of 2 between simulation and experiment.

Validation of the simulation model – heat affected zone

The normally distributed heat source model for mapping the heat induced by the laser (described in WP 3.2) was applied. The obtained simulation results are compared with the etched microsections presented in WP 2.3 for validation purposes. The results are shown in Figure 8. It can be seen, that the width of the heat affected zone in the simulation exhibits a plausible size. In contrast, the shape of the melt track is not mapped adequately by the simulation model.

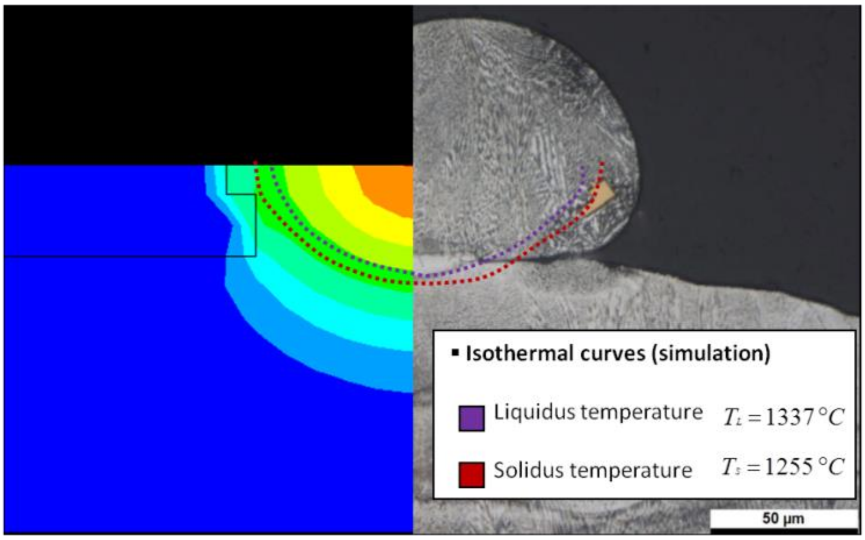

Figure 8: Comparison of the simulation model with an etched microsection of a single melt track. The isothermal curves for the liquidus point (violet) and the solidus point (red) obtained by the simulation are displayed. It can be seen that the shape of the melt track is not mapped adequately by the simulation model. This is caused by the fact that fluid-dynamics within the melt pool are not considered yet. Nevertheless, the width of the heat affected zone in the simulation exhibits a plausible size.

WP 2.5 Optimization cycle for structural model

Recommendations for accuracy enhancement

The accuracy of the simulation model was increased by different approaches. For instance, the mapping of free-formed surfaces was improved compared to the cube-based meshing by the developed customized mesh generation algorithms. As described above, the material model was also adjusted with regard to the consideration of the elastic limit.

Within WP 2.5 various fields of action for further work packages were identified. For instance, it became obvious that the consideration of fluid-dynamics within the melt pool can increase the mapping accuracy of the heat affected zone and the shape of the melt track. Hence, the melt pool dynamics were investigated more precisely within WP 3. Furthermore, in the currently existing simulation model the heat transportation of the powder bed is ignored. Further approaches should consider the thermal effects within the powder bed because this can lead to an improved mapping of the heat balance.

WP 3: Process module

Objectives of WP3 as submitted in Annex I to the GA

- *The measured material data from the previous work package has to be supplemented by the development of adequate material models. With a detailed modelling of the material behavior also influences on the macro level have to be considered.*
- *Compared with the structure model of work package 2 the more precise process mapping within the heat-affected zone should be realized in the simulation to reach more accurate results. Therefore, the development of heat source models as well as the supplement of further detail methods is the objective of this work package.*
- *The results have to be validated with the application of suitable experiments and are sequentially summarized. These data are the starting point for the integrated simulation model.*

WP 3.1 Methods for mapping detailed process characteristics

The powder can be mapped by a continuum approximation, meaning that the powder particles are represented by a solid-like material as presented in [4]. For instance, the heat conductivity and the tensile strengths are considerably reduced compared to solid material. In case the temperature of the powder elements exceeds the liquidus point, these elements change their state to non-powder solid material. Additionally, sensitivity studies showed the influence of powder surrounding the part to be minimal. It was thus excluded from the modeling.

Methods for a detailed process mapping

As described in previous sections of this report, different heat source models exist. They can mainly be distinguished by the way the heat energy is generated. On the one hand a temperature load is prescribed on selected nodes for a given time; on the other hand a (volumetric or surface-related) heat flux density is applied. For the detailed mapping of the beam-material-interaction a heat source model has to be chosen, which takes the beam characteristics and material properties (e. g. absorptivity) into account. The heat generated by the beam can be described mathematically by a rotationally symmetric Gaussian intensity distribution.

Many different physical effects occur in Selective Laser Melting (and laser material processing in general): Amongst others melting and solidification, evaporation, absorption and multiple reflections, free surface flows, flows driven by surface tension gradients (Marangoni flow) and natural convection to name a few. Modelling approaches in ANSYS® CFX simultaneously considering all the occurring effects resulted in instable solver runs or – caused by the very fine temporal and spatial discretization required for a stable solution – resulted in inacceptably high computation times. Hence, a simplified but stable and time-efficient model (neglecting evaporation, free surfaces and Marangoni flows but considering fluid dynamics in the melt pool) was utilized within WP 3.

WP 3.2 Mapping of the heat affected zone into the simulation

Development of customized heat sources

The optical penetration depth of the radiation emitted by the Nd:YAG-laser used in the manufacturing system is in the range of a few nm. The used element size is in the order of magnitude of µm. Hence, it was neglected within a first approach and an area-related heat flux density was used for mapping the beam-solid-interaction. The effective optical penetration depth, however, cannot be ignored within approaches for mapping the beam-powder-interaction due to e. g. multiple reflections of the laser beam within the powder bed. The latter consists of nearly spherical particles in reality but was modelled as a flat and solid-like continuum. Hence, the heat generation in the powder is modelled by a volumetric heat flux density. Thereby, the intensity decreases exponentially with the powder depth. Detailed investigations on the radiation-powder-interaction can be found in [5]. The method developed within AeroSim as well as the used process parameters and the underlying equations are shown in Figure 9.

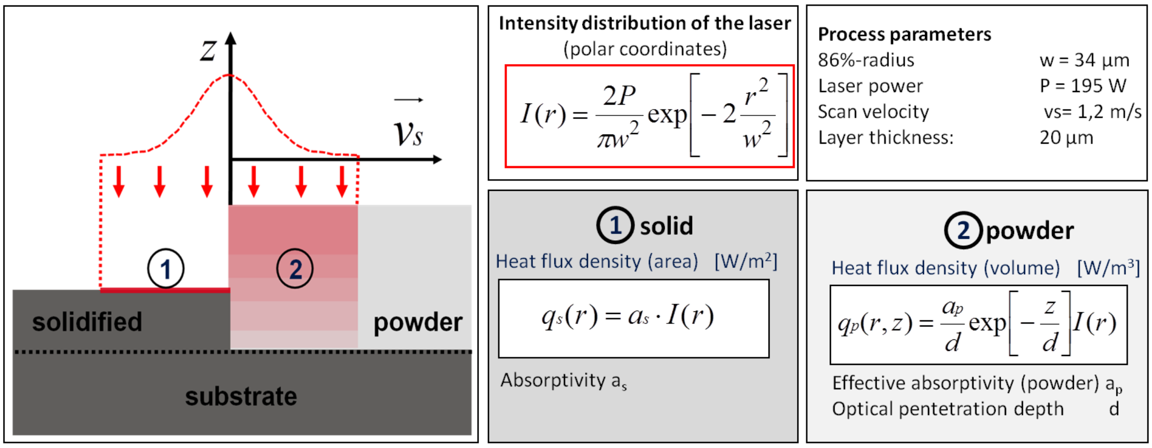

Figure 9: Heat source models for powder and solid areas. The powder is mapped by a continuum approximation on which a volumetric heat flux density is applied for heat generation. The multiple reflections at the surface of the spherical powder particles are taken into account by an effective optical penetration depth. The solidified part areas are heated by an area-related heat flux density due to the fact that the effective optical penetration depth of solid metals is in the range of a few nm.

The above described heat source is applied on a specimen with adiabatic boundary conditions. Within this model no powder exists, which means that only the area-related heat flux density is applied on the topmost nodes of the specimen. For a reduction of the computation time, the symmetry of the problem is taken into account by applying a symmetry plane. The heat is applied as a rotationally symmetric Gaussian distributed heat flux density (power per area) moving along the symmetry plane with a scan velocity of 1.2 m/s. The resulting melt track and the measures of the specimen are shown in Figure 10.

For mapping the heat removal caused by evaporating material the temperature range is limited by a value near the vaporization temperature of nickel, which has the highest vaporization temperature of all alloying elements in Inconel718. Fluid dynamics of the melt pool have not been considered yet.

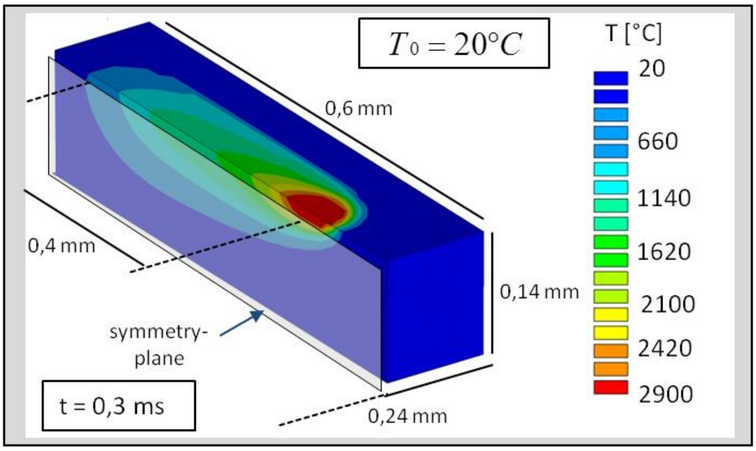

Figure 10: The melt track as a result of the application of a moving Gauss-distributed heat source (area-related heat flux density). The temperature range is limited to the vaporization temperature of nickel, which is the highest of all alloying elements in Inconel718. In order to reduce the computation time, the symmetry of the problem is taken into account.

WP 3.2 Mapping of the heat affected zone into the simulation

The simulation approaches developed within work package 3.1 (mainly based on area-related heat sources on the surface of the specimen) underestimated the real melt pool depth. This indicates the presence of effects related to deep welding ("keyhole mode"), where energy is transported in subjacent part areas by multiple reflections of the laser radiation within the vapor capillarity resulting in increased melt pool depth and changes of the melt pool shape compared to "conduction mode"-laser material processing. It can be expected that the simultaneous consideration of all relevant physical effects during keyhole formation in the simulation would result in high computation times. As a consequence, a simplified and time-efficient heat generation model is introduced based on an approach combining area-related and volumetric heat sources to achieve a close-to-reality melt pool shape. Here, the heat transportation in subjacent part areas by the above mentioned effects occurring in "keyhole-mode" laser material processing are modelled by a cylindrical, volumetric heat flux density in the center of the heat source surrounded by an area-related heat flux density applied on the surface of the specimen. A schematic representation is shown in Figure 11.

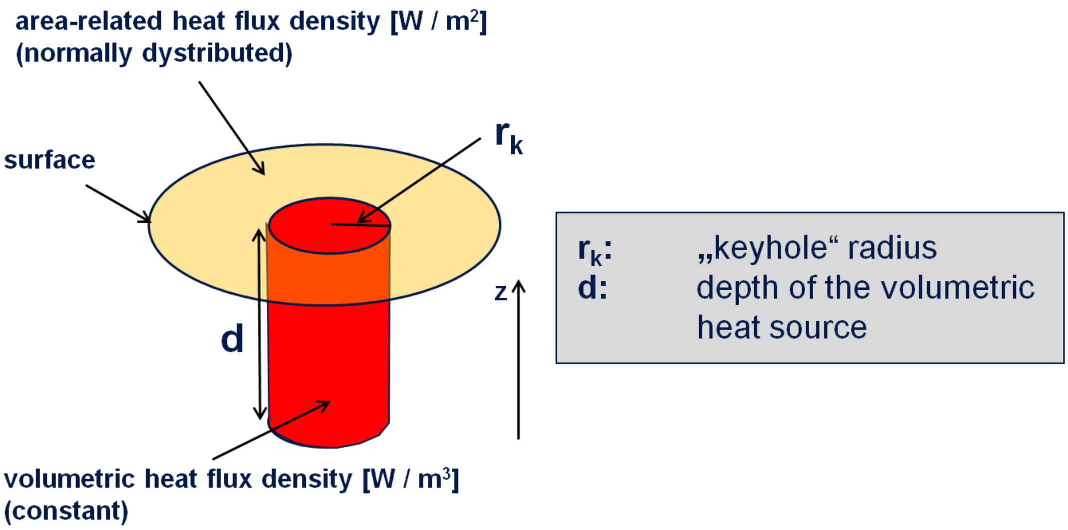

Figure 11: Representation of the combined heat source model consisting of an area-related, normally distributed heat flux density on the surface of the specimen and a volumetric heat flux density with cylindrical shape

The radius r_k was chosen to be half the beam radius (86 %-radius, i. e. the term “beam radius” refers to the radius of the circle that encloses an area where 86 % of the beam’s power arrive), so 39 % (under the assumption of a Gauss distribution, a circle with only half of the beam radius encloses an area where 39 % of the beam power arrive)of the laser power is deposited within the cylindrical volume region. Inside the cylinder the heat generation is assumed to be constant. The depth d was set to 70 µm. Both the radius r_k and the depth of the cylinder d were chosen based on knowledge obtained by experimental results. To increase the accuracy of the heat source model, future work should focus on the heat source calibration by utilizing existing analytical and numerical models for the prediction of the melt pool shape, the process efficiency and the keyhole geometry.

The volumetric heat flux density q within the cylinder was calculated using

$$q = 0.39\,\alpha\,\frac{P_0}{r_k^2 \pi d}\,,$$

where P_0 is the laser power and α is the absorptivity. The factor 0.39 results from the fact, that 39 % of the laser power is deposited within the circle with half the beam radius (86%-radius).

WP 3.3 Application of different heat sources

The heat source models described in the previous section have been compared concerning the resulting melt pool shape and temperature-field near the heat source. Figure 12 shows the melt pool geometry obtained from the simulation for the two cases “hybrid“ and “area-related” heat generation.

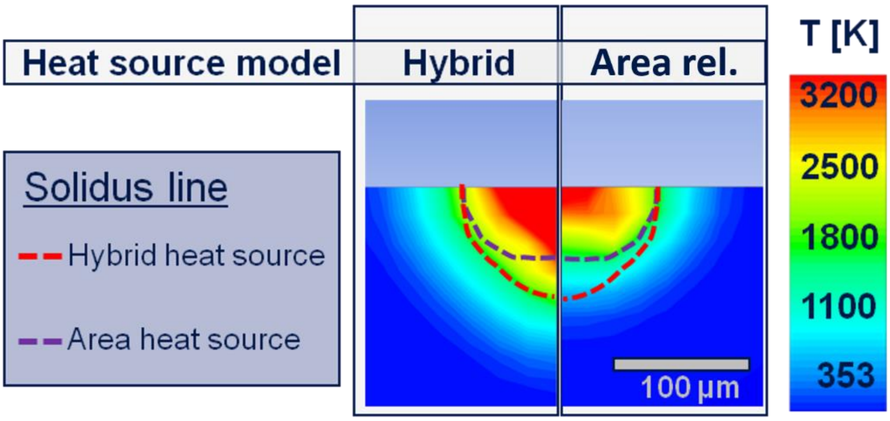

Figure 12: Comparison of simulation results by utilizing a hybrid and an area-related heat source model (front view)

As expected, the melt pool depth of the “hybrid” model is larger than the melt pool depth of the model with a heat application only on the surface of the specimen.

WP 3.4 Validation of modelled material and process behavior with experimental results

As it can be seen in Figure 13, the simulation result (utilizing the hybrid heat source model mentioned in the previous section) is in appropriate accordance with the experimentally determined melt pool depth and shape considering the presented approximations of the simulation model (e. g. neglecting of evaporation and free surface flows).

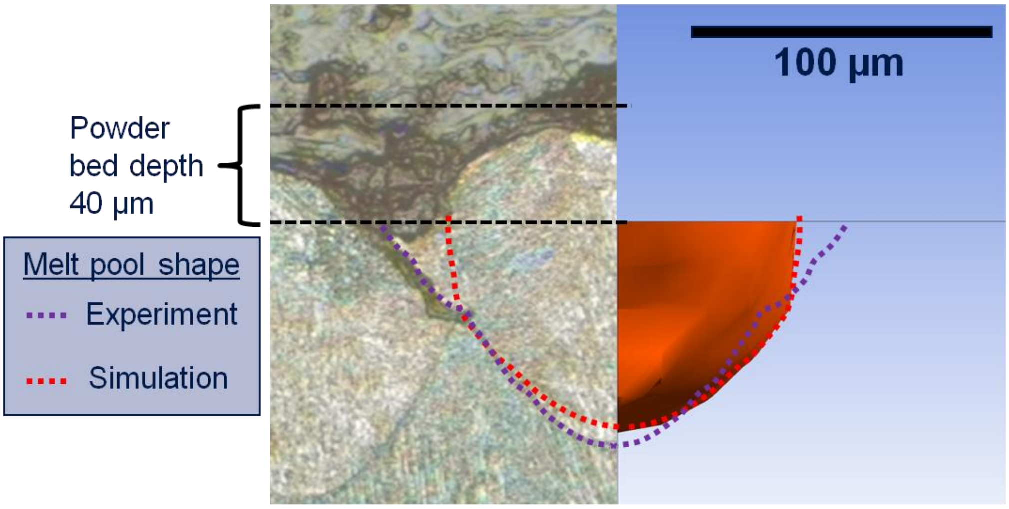

Figure 13: Comparison of simulation results from the hybrid heat source model with a microsection

WP 4 Integrated simulation model

Objectives of WP 4 as submitted in Annex I to the GA:

- *In work package 4 the methods defined in work package 2 (structural model) and work package 3 (process model) have to be combined into an integrated simulation model. Accordingly the methods have to be linked with each other.*
- *The integrated simulation model has to be checked with regard to the calculation accuracy. This is done by using appropriate benchmark geometries.*
- *The benefit for the user has to be pointed out employing this integrated simulation model.*

WP 4.1 Methods for coupling and visualization of the simulation disciplines

Methods for coupling the simulation disciplines under consideration of the different levels of detail were investigated. Furthermore, suitable methods for measuring the structural behavior were chosen and methods for post processing the simulation were investigated. Figure 14 illustrates the method chosen within AeroSim to couple the different simulation disciplines.

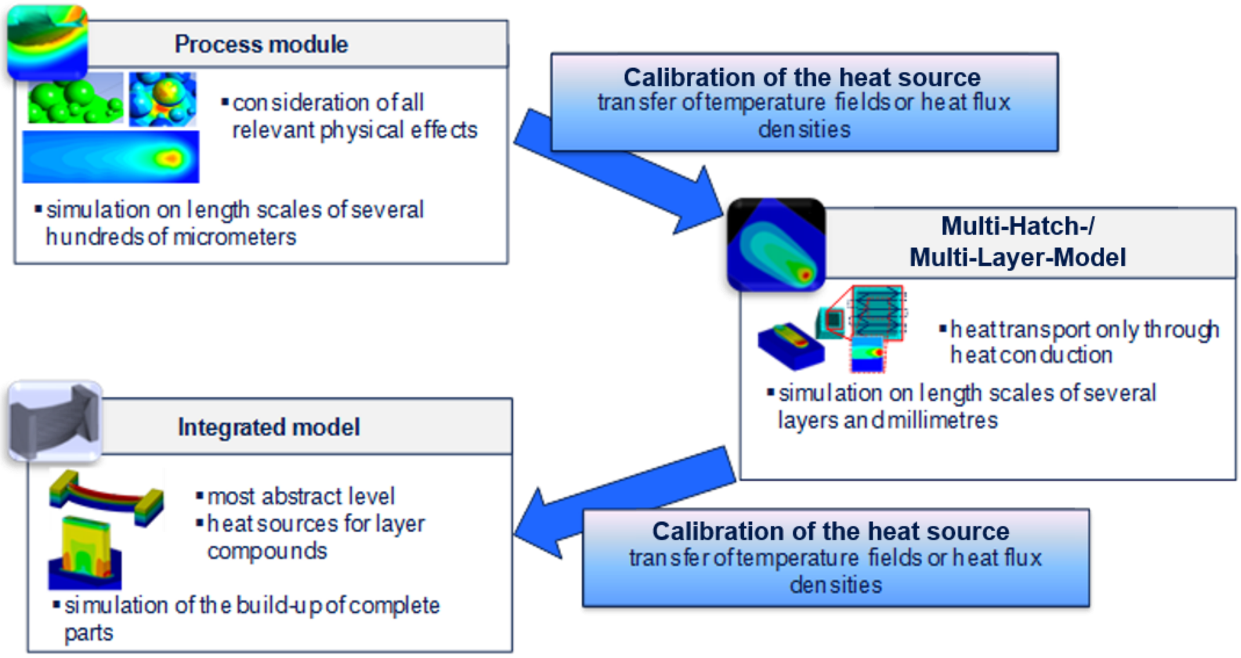

Figure 14: Method for coupling and visualization of the simulation disciplines

Basically, a calibration of the heat source is performed based on the results of more detailed modelling approaches. By doing so, the energy balance is fulfilled. The structural behavior is investigated by 3-D-imaging of parts in terms of deformations.

WP 4.2 Development of interfaces and integration of MTU Aero Engines AG specific demands

All relevant interfaces to realize the method illustrated in Figure 14 are developed.

In order to consider MTU Aero Engines AG specific requirements, interfaces to process machine data (so called CLI-data) of the laser beam melting system EOS M280 were developed. Based on CLI-data it is now possible to model the part's geometry, cf. Figure 15. The usage of CLI-data is based on an evaluation of possible methods of geometry modelling which was also performed within the second project year.

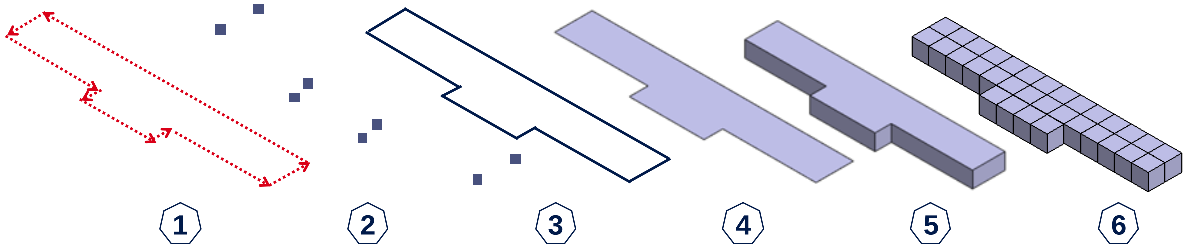

Figure 15: Method for CLI-based geometry modelling [6]

Furthermore, heat input modelling can be performed according to the applied scan strategy. In case of the used EOS Systems, this is typically the strip-wise exposure. Figure 16 gives an overview of all developed methods within AeroSim.

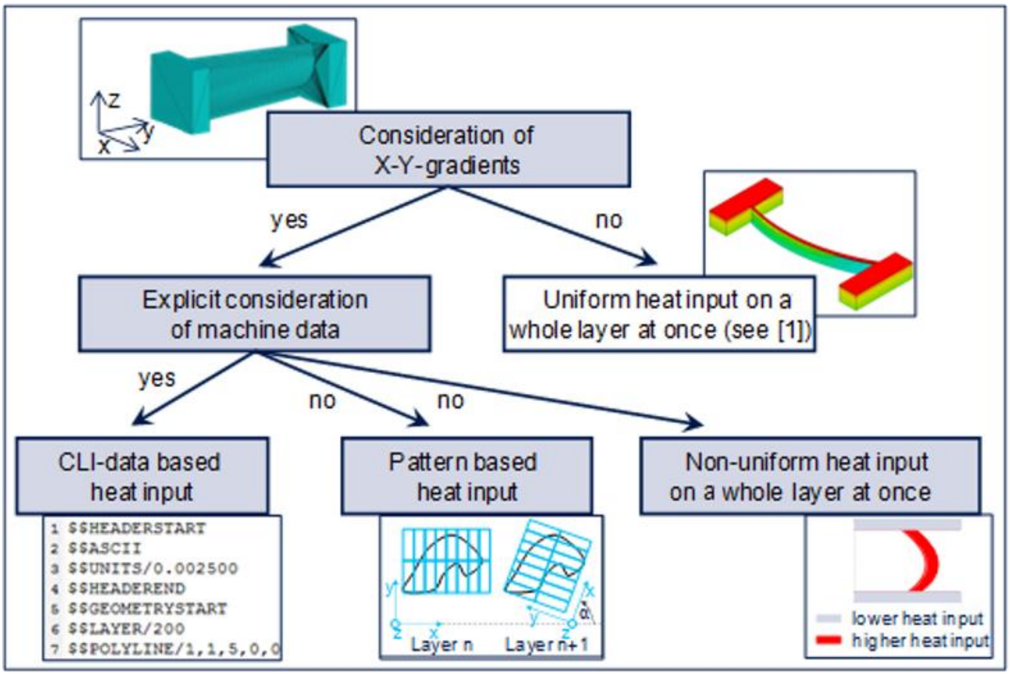

Figure 16: Methods for heat input modelling [7]

In the most abstract level of detail, a uniform heat input is applied on the whole layer compound at once. Thereby, the applied scan strategy cannot be considered. This method is well-known in literature. Within AeroSim, three additional methods were developed, which enable a consideration of temperature gradients perpendicular to the build direction. Especially the CLI-data based heat input modelling is an approach that allows to vary the level of detail for every simulation run.

WP 4.3 Definition of benchmark geometries and experimental studies

A test plan was worked out which focuses on Inconel parts. However, two build plates with titanium specimens were also planned and built at the *iwb*. The manufacturing of the Inconel specimens within WP 4.4 was performed at MTU Aero Engines AG. Figure 17 shows the test plan.

Part	**Material**		**Scan velocity filigree areas**		**Wire cutting**
	Inconel	**Titan**	**normal**	**fast**	
Turbine blade – configuration 1	■	■	■	■	■
Turbine blade – configuration 2	■		■	■	■
Turbine blade – configuration 3	■		■	■	■
Boroskopauge – configuration 1	■		■		■
Boroskopauge – configuration 2	■		■		
Boroskopauge – configuration 3	■		■		
Thin-walled angle piece	■	■	■		
Thick-walled angle piece	■	■	■		
Rectangular solid – build direction 1	■	■	■		
Rectangular solid – build direction 2	■	■	■		
Brigdge geometrie configuration 1-3	■	■	■		■

Figure 17: Test plan of WP 4.3. All filled fields indicate that the corresponding experiment was conducted. The Bridge geometry configuration 1-3 was, for example, built in Inconel and Titanium with normal scan velocity in filigree areas and separated from the build plate by means of wire cutting.

Besides parts with simple geometries like angle pieces and rectangular solids, two industrially relevant parts were investigated (turbine blade and maintenance opening). In order to increase dimensional accuracy, a configuration was tested for which the scanning velocity was adjusted in the free-formed filigree part area of the turbine blade. This is based on numerical investigations which allowed the detection of heat accumulations in this part area. These were assumed to be responsible for the deformation. To identify filigree part areas, an algorithm was developed within AeroSim and programmed in C++-language [7].

In order to further the understanding of temperature gradients, heat accumulation and structural behavior (deformation and residual stresses) bridge test geometries were developed, which exhibit a different area for heat conduction in each bridge pillar, cf. Figure 18. As a reference, a symmetric bridge was also considered within this test plan.

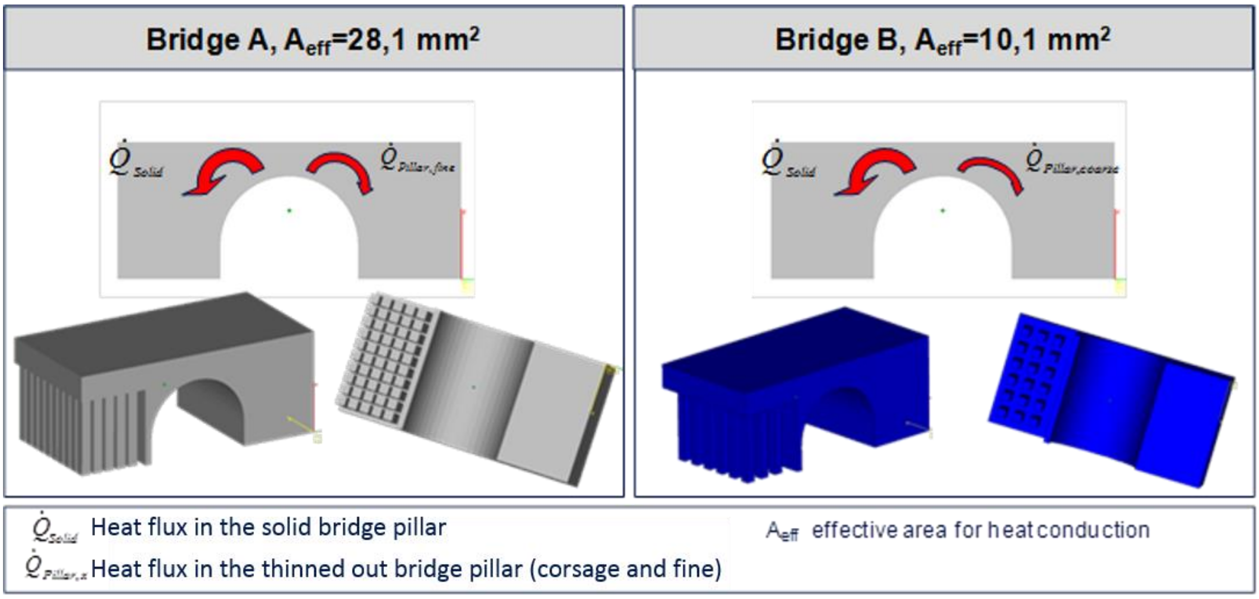

Figure 18: Bridge specimens

WP 4.4 Manufacturing of parts and comparison with simulation

As explained in the section above, an improvement in terms of the dimensional accuracy was expected by adjusting the scan velocity in the free-formed filigree part area of the turbine blade. Figure 19 proves that this was successful. A reduction in the maximum distortion of 6 % (under consideration of the standard deviation of 2 %) could be achieved.

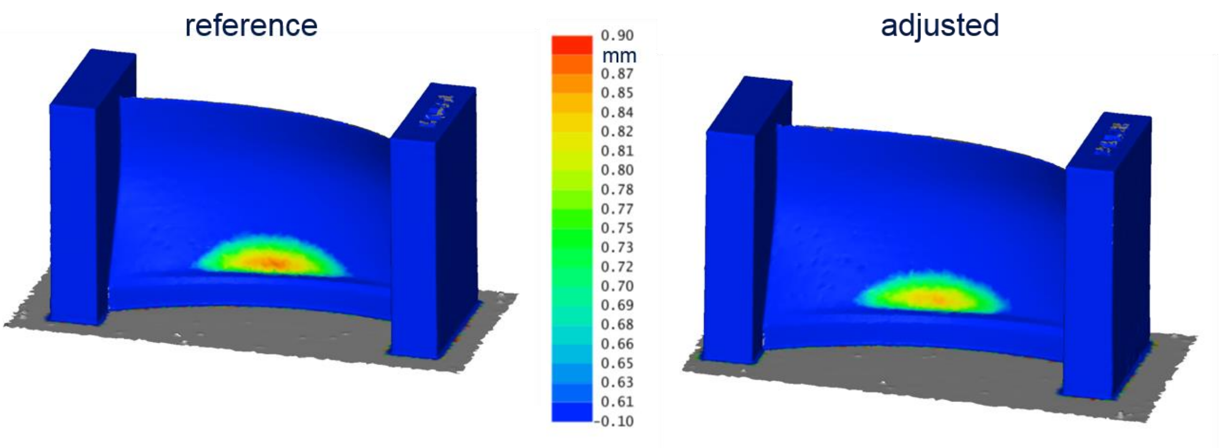

Figure 19: User benefit of adjusting the scan velocity in filigree part areas

To validate the simulations, two different quantities are measurable. The deformation of built-up parts can be measured with optical and tactile systems. Additionally, different techniques that are presented and discussed later, allow the assessment of the residual stress state of the manufactured parts. Over the course of project year 3, multiple parts were manufactured and compared to the results of corresponding simulations. With the magnitude of deformations being close to the order of the measuring inaccuracy of the systems available at the *iwb*, the validation of deformations of new results was carried out by MTU Aero Engines AG staff in the form of oral feedback in the project meetings. Aside from a set of limited features like long overhanging structures, the agreement was found to be sufficient (Figure 20). The user benefit for all project partners to gain an understanding of the transient development of the thermal and mechanical key indicators became apparent. Thus, the level of comprehension for the formation of residual stresses was increased.

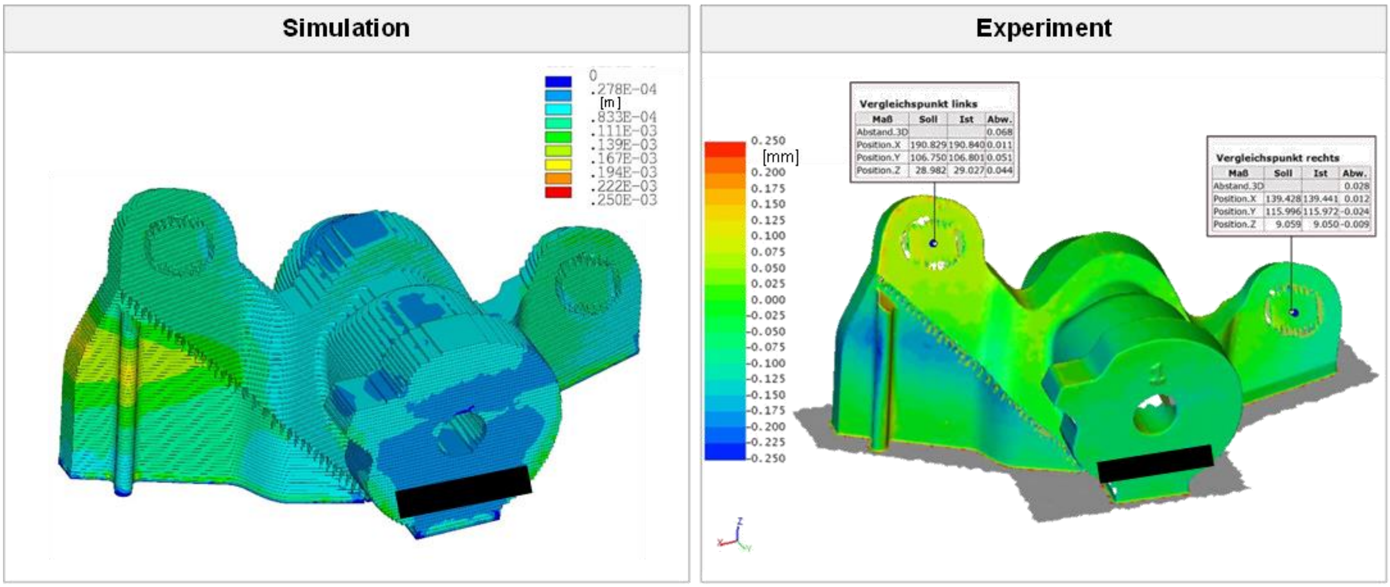

Figure 20: Aero engine service opening with teeth support. Comparison of simulation and manufacturing result.

In terms of residual stresses, multiple forms of validation measurements were used, including neutron diffractometry experiments at the Heinz-Maier-Leibnitz Zentrum in Garching/Munich. Additionally, MTU Aero Engines AG supported these validation efforts by providing results of hole drilling trials on the same samples. These results will be confirmed by x-ray diffraction trials in the near future and the entirety of the results is intended to be published in order to further the understanding of residual stresses in selective laser melting.

A standing cuboid geometry (40x10x40 mm, with z aligned to the build-up direction reaching 40 mm and x along the longer edge) was chosen as a first validation example. The Inconel 718 part was manufactured on an EOS M280-system at MTU Aero Engines AG with standard parameters. The experimental values were gathered by means of neutron diffraction at the STRESS-SPEC instrument of the Heinz Maier-Leibnitz Zentrum in Garching, Germany. Preliminary results show good agreement between experimental and numerical results. [8]

To enable a comparison of the different assessments, two different forms of diagrams are chosen. First, a simple scatter plot shows the level of agreement between simulation and neutron diffractometry (cf. Figure 21) and second cross sections of the block geometries show results from the simulation (colour plot), from the neutron diffractometry (Sx, Sy, Sz) and from the hole drilling method (Arabic numerals) results (cf. Figure 22).

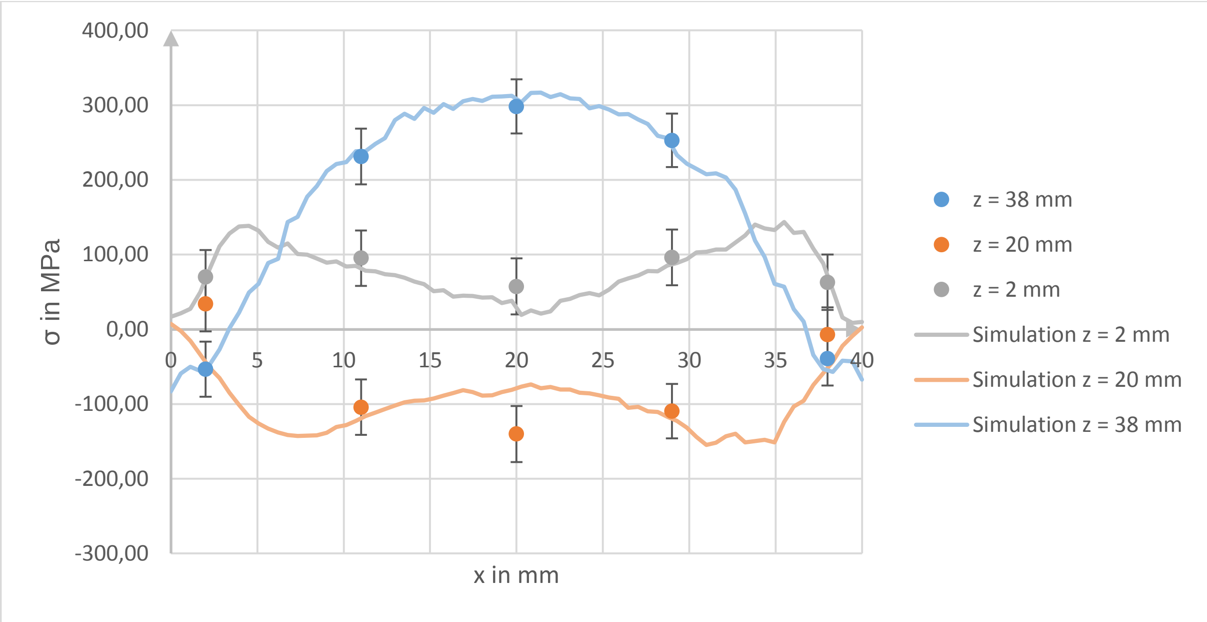

Figure 21: Residual stresses in a standing cuboid geometry for three different height levels. The measured values in the actual sample are provided as dots and the respective error bars represent the fitting uncertainty. The continuous lines are extracted from the simulation by averaging over all nodal values within a sample volume equivalent to that of the neutron diffractometry experiments.

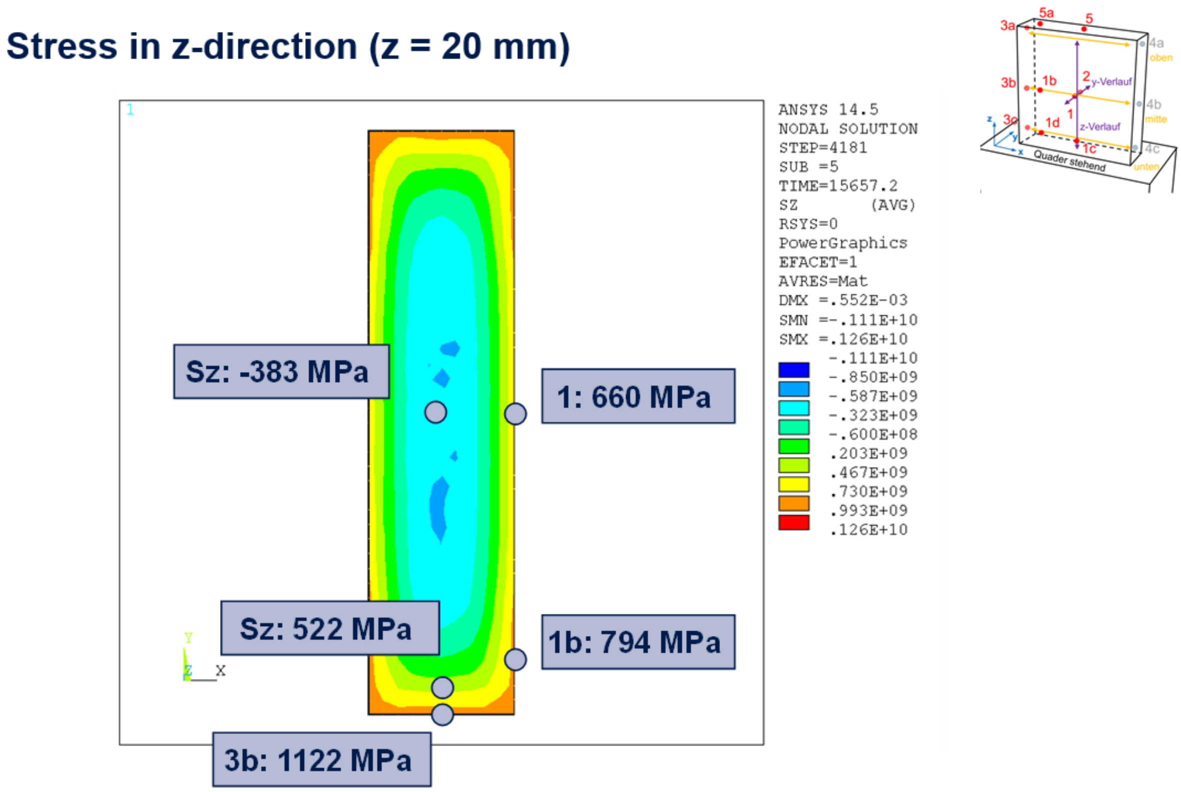

Figure 22: Stress in normal direction in the middle of the standing cuboid geometry; comparison of results from the neutron diffractometry, from the drill hole methods and from the simulation

WP 4.5 Optimization cycle for enhancing the results accuracy

To raise the accuracy of the results, it was determined, that the representation of the geometry by the mesh needs improvement. With the robust machine-data based meshing approach, a better agreement between mesh and geometry is not feasible. As a consequence, a new CAD-data based meshing process chain was developed (cf. Figure 23).

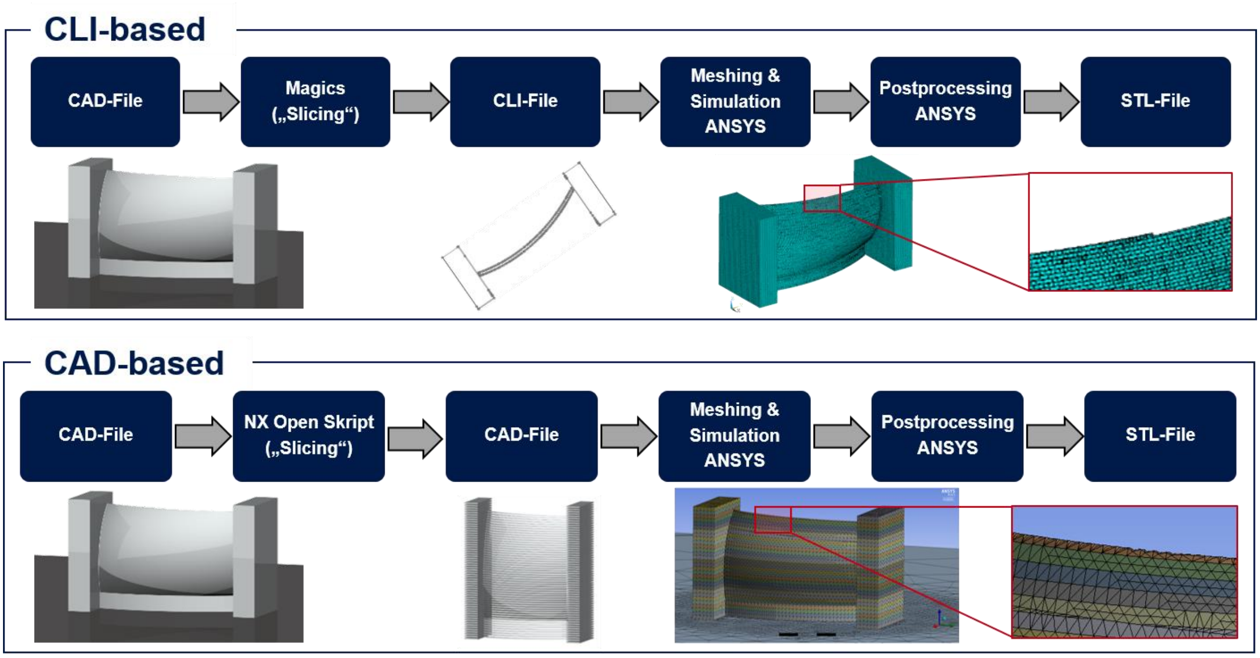

Figure 23: Comparison of the two available data chains within the AeroSim simulation tool

In a first step the volume is sliced into layers with a custom program extension for the Siemens NX Software Suite. Subsequently, the layered geometry is meshed in ANSYS Workbench, creating a coherent mesh with nodes lying at distinct levels in build-up direction. Hexahedron as well as tetrahedron elements can be chosen, allowing for more flexibility for the user. A different meshing strategy is presented by [9], where the part is meshed by superimposing a 3-dimensional grid and a subsequent rearrangement of the nodes

This alternative approach also enables a software supported process chain in terms of improving accuracy. While results of the CLI-based chain can only serve as a reference while manually changing the input geometry, the inverted deformation results of the CAD-based chain can be used to refit the initial model's areas directly.

WP 5: Validation, optimization and implementation

Objectives of WP 5 as submitted in Annex I to the GA

- *With developing adequate optimization strategies it should be possible to optimize process parameters by using the integrated simulation model.*
- *The integrated simulation model from work package 4 and the optimization methods have to be combined to a complete process chain. Thereby an automatic and time-efficient data flow should be realized using appropriate interfaces.*
- *The optimized build-up strategy should be transferred into the hard- and software environment of the* MTU Aero Engines AG *automatically to assure a high efficiency.*

- *The process chain should be evaluated in terms of its functionality and the fulfillment of the requirements previously defined with MTU Aero Engines AG. The manufacturing of a part using conventional as well as optimized process parameters should permit a direct comparison, by which the user´s benefit should become visible applying this process chain.*

WP 5.1 Methods for simulation-based optimization

Analysis of systems for simulation-diagnosis

The developed tool for simulation diagnosis provides information about the current simulation run. It can be used for an easy to understand monitoring of the geometry import, the type and size of the existing elements and other important settings and parameters. Thereby, inaccuracies and imperfections can be identified by the user without an additional appropriation of simulation expertise or programming knowledge, which is important because the tool should be utilized by machine operators.

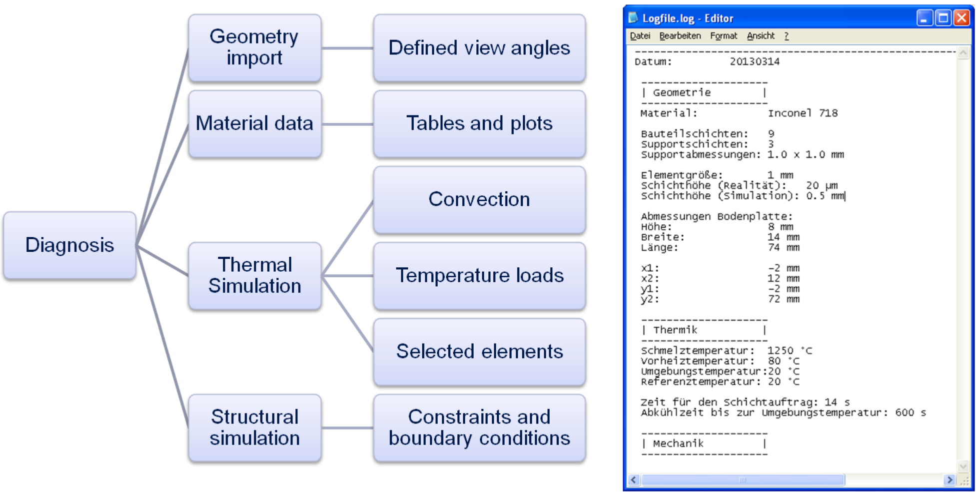

Figure 26: Exemplary overview of the information provided by the simulation diagnosis tool (left) and first realization of the user interface (right). With the diagnosis tool, problems can be identified by the user without being a simulation expert.

WP 5.2 Development of optimization algorithms and adaption to a process-chain

In order to improve the accuracy of parts manufactured by selective laser melting, an optimization algorithm was introduced. The basic idea is to pre-warp the initial geometry for the manufacturing process in order to yield a part closer to the desired geometry in an iterative fashion until the manufacturing matches said geometry within the determined tolerances. The concept of pre-warping the part to compensate for the resulting dimensional deviations is well-established in non-metal and metal based additive manufacturing, whether this results from process or machine specific factors [10, 11]. In most cases, this pre-warping process involves multiple manufacturing steps and respective measurements of distortions. The corresponding convergence and duration depend on the experience of the user and the availability of the technical equipment. Another possibility is to substitute the actual build-up step for a manufacturing simulation, establishing the transition to a simulation-supported process chain. Commonly, this method involves a single-stage adjustment of the input CAD-file by inverting the warpage of the manufacturing result, i. e. the dimensional deviations. However, the non-linear manufacturing process is not likely to yield the desired geometry at the first iteration. In order to further the value of assistance of the simulation to the AM user, an iterative approach to minimize dimensional deviations was investigated. Additionally, a simulation-supported process is only viable if the designated user's abilities are coherent with the requirements of the described process, creating a need for automatization.

Figure 24 presents exemplary results of the simulation-based pre-warping process. The first manufacturing simulation (Iteration 0) reveals significant dimensional deviations compared to the input geometry. For this simple geometry, the second iteration already results in a significant decrease of the dimensional deviations.

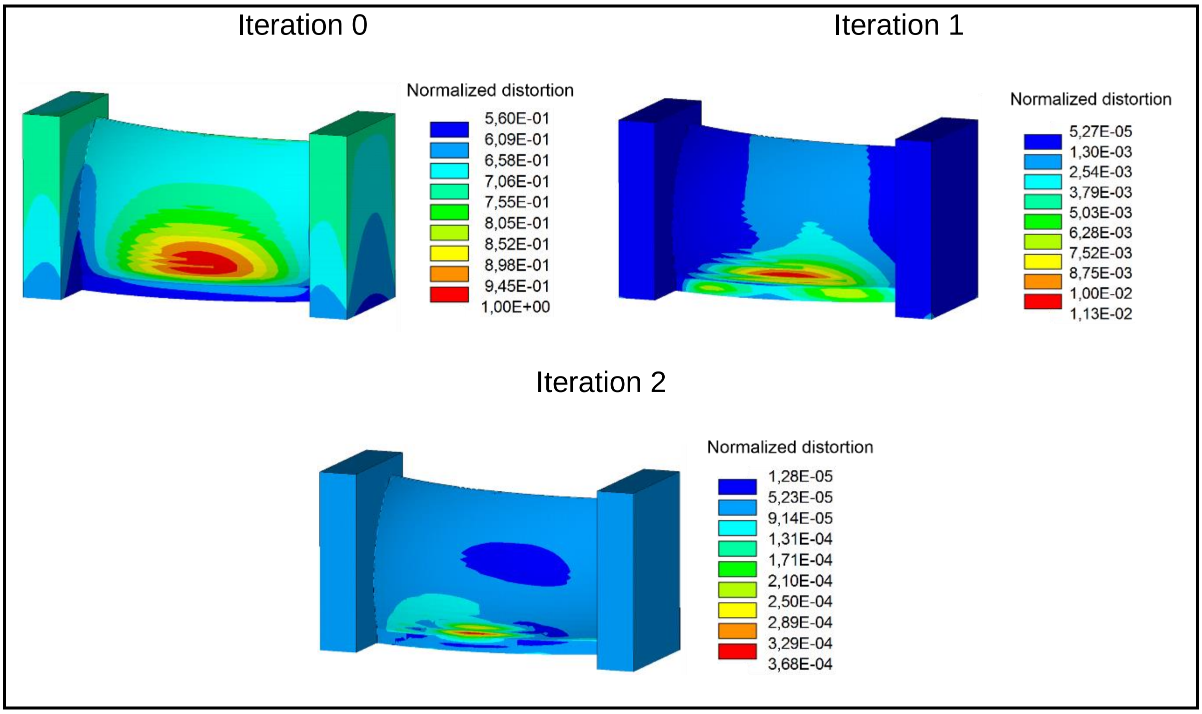

Figure 24: Development of the simulated dimensional deviations of the built-up part over the course of the iterations, the given distortion is normalized by the maximum deviation of the first simulation (Iteration 0, maximum deviation 0.128E-03). A manufacturing process with standard parameters was simulated.

The presented process was implemented into the simulation system and only the initial mesh is used for the simulation. Upon termination of the n-th simulation run, the initial mesh is distorted according to the previously mentioned pre-warping logic and then the result of this is used as input for the subsequent run. This consistent mesh facilitates further processing. The error resulting from the distorted level of heat application (cf. Figure 25) is deemed negligible due to the limited size of the distortions in proportion to the height of the layer compounds.

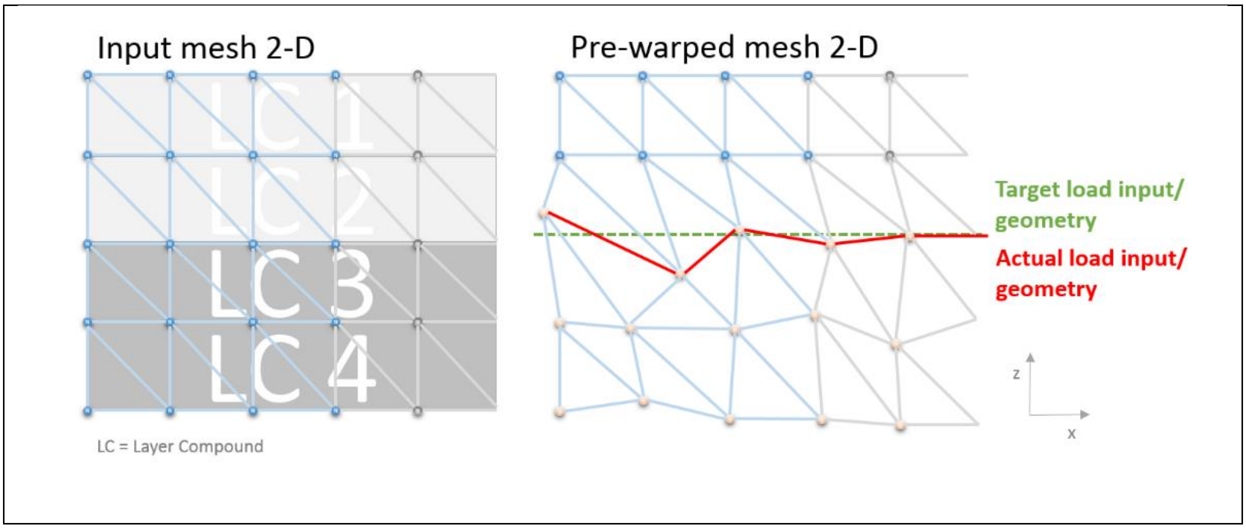

Figure 25: Comparison of target versus actual z-level of the heat input for a pre-warped mesh, four layer compounds are shown and the proportions are exaggerated to visualize the effect.

To allow for better monitoring of the pre-deformation process, the functionality of the software tool was enhanced by calculating and displaying distortions with respect to the initial (target geometry) rather than the input (pre-deformed geometry except for the first iteration) design. This enables quick evaluation and confirmation of the effectiveness of the pre-warping process step-by-step up to the final design suggestion. Additionally, it is possible to directly extract an STL file of the pre-warped geometry for a streamlined manufacturing process.

WP 5.3 Functional test of the process-chain

The process chain was used to simulate many different parts. The results are shown in the following. The functional test of the process-chain was actively supported by MTU Aero Engines AG staff with helpful feedback concerning both of the data chains and their usability. The tests deemed the CLI-based chain to be more robust and easier to use, but impractical for further data processing and with higher calculation times. The CAD-based process chain was found to yield results in a more useful way and typically a lot faster, but with a higher effort on the side of the user. An additional reduction of the calculation time was achieved by using the automatic time stepping function of the solver in connection with a suitable start step size. Figure 26 shows the results for the different approaches and different solver settings.

CLI-Import

	None		
100 %	Thermal	53min	9,17 %
	Mech.	8h 45min	90,83 %
	Total	**9h 38min**	
63,49 %	**Shared-Memory Parallel (SMP)**		
	Total	**6h 07min**	
40,48 %	**Distributed Computing (MPP)**		
	Total	**3h 54min**	

CAD-Import

None			
Thermal	1h 03min	16,71 %	65,22 %
Mech.	5h 14min	83,29 %	
Total	**6h 17min**		
Shared-Memory Parallel (SMP)			33,04 %
Total	**3h 11min**		
Distributed Computing (MPP)			17,99 %
Total	**1h 44min**		
MPP und AUTOTS			9,52 %
Thermal	10min	18,18 %	
Mech.	45min	81,82 %	
Total	**55min**		

Figure 26: Calculation times for the different approaches and different solver settings

WP 5.4 Manufacturing of benchmark geometries and comparison with simulation results

The simulation results showed a significant reduction of deformation with respect to the initial, i. e. the desired, geometry (cf. Figure 24). Due to a suboptimal load application[1] within the CAD-based process chain, the iterative approach did not yield valuable results. However, the results shown in Figure 27 indicate that a single step already increases the result accuracy by 41%.

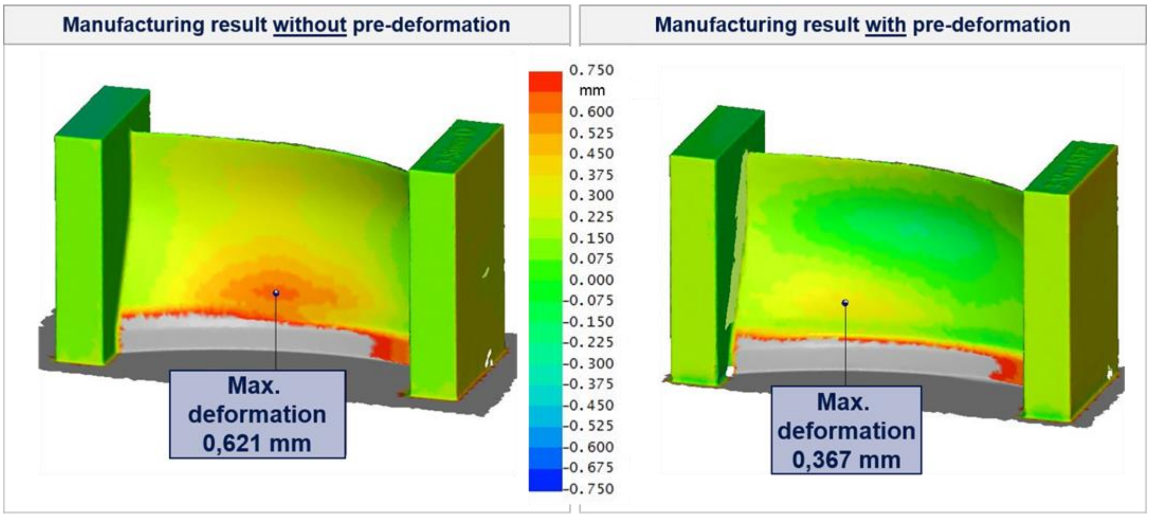

Figure 27: Comparison of manufacturing results without pre-deformation and with pre-deformation

WP 5.5 User manual and training

In order to support the implementation of the AeroSim simulation tool at the MTU Aero Engines AG, 5 trainings (cf. Table 3) were held at MTU Aero Engines AG in a workshop like environment. User manuals for all important aspects of the process chain were developed and transferred to MTU Aero Engines AG. The staff of *iwb* was supported by MTU Aero Engines AG IT professionals concerning aspects unique to the IT infrastructure at MTU Aero Engines AG, so that the designated users gained insights into the way of working with the developed tool in their own IT infrastructure.

[1] The challenge occurred with the introduction of the CAD-based data chain. Within the CLI-based data chain, all layer compounds comprise only one layer of elements, i. e. one layer of nodes on the top of the current layer compound. In contrast, depending on the magnitude of geometrical features, the CAD-based models usually require multiple elements per layer compound in height direction. That means, that by only applying load to the top layer of nodes does not create the same temperature gradient along the height of the layer compound than it does in the CLI-based models. This was fixed by applying a linear gradient along the height of the layer compound rather than only the solidus temperature at the top. The necessary temperatures are computed by linear interpolation according to the z-level of the nodes.

Table 3: Training sessions to transfer the developed tool to the MTU Aero Engines AG

Training Day	Date	Content
1	06.05.2015	Introduction of the MTU IT infrastructure (MTU) Introduction of ANSYS; APDL macro structure Diagnosis and monitoring CLI-Import I
2	10.06.2015	CLI-Import II STL-Export
3	30.06.2015	CAD-Import I Data preparation in NX & ANSYS Workbench
4	08.07.2015	CAD-Import II Data preparation in NX & ANSYS Workbench Meshing STL-Export
5	24.07.2015	Questions and open issues

Potential impact

Expected impacts

The process chain, containing the integrated simulation model and the optimization methods, was validated based on components of the SAGE4 full engine. In consequence, the main objective of using the process chain for aerospace applications in general and the selected parts in particular, is fulfilled.

In order to ensure long-term prospects, to maintain independence, to spread business hazards and to preserve jobs in European companies, the development and realization of innovations is important. In this respect, the project results exhibit a significant impact concerning competitive advantages for European companies in the future. Therefore, EU based companies can gather essential advantages through the application of the process chain which was developed within this project. The advantages of the project results for the industry are presented and also the impact on the employment situation in the European Union is described. By using the developed process chain, significant advantages of companies concerning the employment of additional staff for the simulation-based qualification process are expected. The *iwb* application center Augsburg has enabled students of the Technische Universitaet Muenchen to work on innovative scientific topics within the scope of lectures, internships and student research. Additionally, within the framework of this project, the students also supported the research staff in the development of the process chain. Thus, a systematic, broad-based transmission of knowledge was realized.

Furthermore, the process chain to simulate the warpage of parts manufactured by selective laser melting allows for a virtual process design with the usage of digital tools. Therefore, important resources can be saved, fulfilling the underlying goal of a more resource-efficient, production.

Benefits for the European industry

Currently, the production of functional parts is a domain of conventional forming processes (e. g. forging, etc.) and cutting technologies (e. g. milling, lathing, etc.). The required part quality and material properties determine whether a technology is used or not. The raw material for the named technologies is typically provided in the form of block or profile geometries, which are then machined toward the final geometry. The consequences are high expenses for the handling and a high level of material waste.

Furthermore, the situation for companies in Europe has changed drastically in recent years due to a diversification of economic conditions. The reason for these accelerating environmental changes are various and can also be associated to the increased globalization. Through the associated internationalization of the markets, more and more product providers exist and a unique selling proposition of a company can only be reached by developing innovative products [12].

Thus, a resource efficient, fast and cost-effective supply of the products to the market is important for an economical production of parts in the future [13]. Due to changed framework conditions a manufacturing technology should be chosen, which can be used in a wide range of production tasks and with which the highest possible production efficiency can be reached. This is also one of the reasons why the demand for additive manufacturing (layered production of a 3D-geometry) rises significantly, like it is shown in Figure 27.

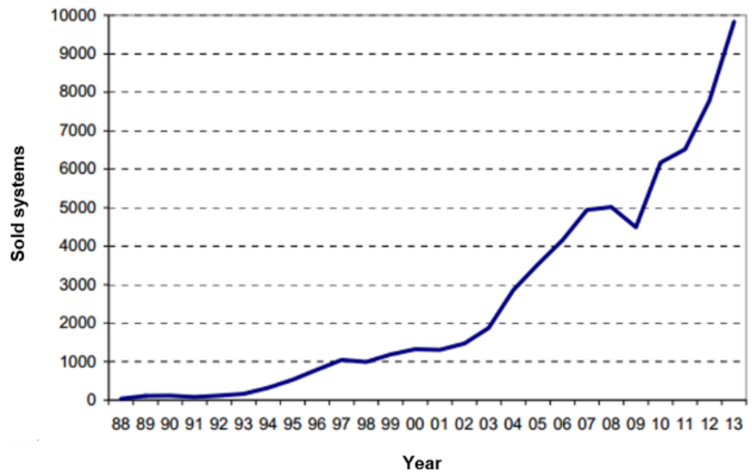

Figure 27: Worldwide sales figures of additive manufacturing systems above $5,000 between 1988 and 2013 [14]

The advantages of layered manufacturing are diverse. With this manufacturing technology a reduced material consumption due to the usage of powder materials as raw material is existing. Only the actually needed material is used for generating the part and the remaining material can be reused with almost no further processes. Furthermore, the manufacturing of complex parts (e. g. with undercuts) is feasible. This enables the manufacturing of parts with a high potential in terms of weight reduction (e. g. with hollows). This characteristic is especially decisive for the aerospace industry. In consequence, innovative lightweight structure can be produced resource efficient even if the part geometry is complex. Furthermore, the applicability in this industry sector is manifold through the number of available materials [15].

For turbine manufacturers the high complexity and the necessity of functional integration of produced parts pose important requirements on the used materials and the manufacturing technology. High process reliability and therefore a high reproducibility of parts is essential to the economical usage of these technologies in the series production. Therefore a high process understanding as well as a correct choice of process parameters (e. g. laser power, laser beam deflection) is required to ensure repeatable part quality. Due to the variety of influencing variables on the production process, this objective is not always achievable. For the requirements of the aerospace industry the currently employed procedures are not acceptable because of the high spreading of the reachable process reliability and stability. The broad-ranged usage of this technology for the manufacturing of the geared turbofan engine, i. e. for realizing components that enable a reduction of fuel consumption noise emissions, is therefore not possible under these conditions.

Therefore, the application of digital tools for the process analysis and for the improvement of part characteristics before the actual manufacturing process is of essential importance. With the developed process chain, consisting of the integrated simulation model and the simulation-based optimization system, it is possible to design the production process with minimized resource usage and thus to start an optimized production. Thus, the qualification of the manufacturing process in order to yield parts without significant dimensional deviations can be decoupled from the actual hardware [8]. Material and system costs for the manufacturing of advanced GTF demonstrators can be saved.

The research results of this project represent essential advantages for the aerospace industry as well as other industry sectors. With the successful usage of the knowledge generated within this research project, European companies can reach unique selling propositions [12]. Therefore, decisive advantages for EU companies over the worldwide competition are generated.

Creation of workplaces in the EU

The iwb application center Augsburg of the Technische Universitaet Muenchen benefits significantly from this project. The knowledge for the dimensioning of manufacturing processes through digital tools has been increased significantly. Thus, the *iwb* application center Augsburg regards itself as a technology transfer center between academia and industry. Therefore, a cooperation of companies and the iwb is possible both in research and industrial projects. The project results are used to transfer the knowledge into industrial companies. This directly creates new workplaces for European companies that work together with the iwb application center Augsburg.

Apart from this, further dissemination activities are executed by the iwb to inform other companies about the research results. With a successful usage of the project results, new workplaces within European companies in the sector of quality or process control will emerge.

The *iwb* also benefits from this project in terms of personnel. Within this project, three research assistants were working intensively on the topics of this project with the objective of writing a dissertation.

Teaching and advanced training

Furthermore, the project enabled numerous students to support the project work. The gained contents are used after project termination for the definition of innovative contents for internships and lectures. Additionally, extensive further education and training of the students, especially in this area are ensured.

In further workshops, organized by the iwb application center, companies should benefit from the knowledge transfer concerning the project results. Therefore, important competitive advantages for the participants can be achieved.

Green production

As mentioned above, additive manufacturing contributes to the realization of a resource efficient production. Only the raw material that forms the resulting part is solidified and all remaining metal powder can be reused after sieving. The process chain, consisting of the integrated simulation model and the simulation-based optimization system, can help to reduce production errors through the virtual process qualification. Material and equipment costs can be saved significantly during the production.

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Use and dissemination of foreground

Section A (public)

This section includes two templates

- Template A1: List of all scientific (peer reviewed) publications relating to the foreground of the project.
- Template A2: List of all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters).

These tables are cumulative, which means that they should always show all publications and activities from the beginning until after the end of the project. Updates are possible at any time.

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
1	*Simulation of the Laser Beam Melting Process – Approaches for an Efficient Modelling of the Beam-material Interaction*	*Seidel, Christian*	*Procedia CIRP*	*25*	*Elsevier B.V.*		*2014*	*pp. 146 - 153*	http://dx.doi.org/10.1016/j.procir.2014.10.023	yes
2	*Investigations on temperature fields during laser beam melting by means of process monitoring and multiscale process modelling*	*Schilp, Johannes*	*Advances in Mechanical Engineering*	*Vol 6, 2014*	*Hindawi Publishing Corporation*		*2014*		http://dx.doi.org/10.1155/2014/217584	yes

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
1	*Conference*	*CADFEM GmbH*	*ANSYS Conference & 30. CADFEM Users Meeting*	*24 – 26 October 2012*	*Kassel*	*Scientific Community, Industry*	*900*	*Worldwide*
2	*Publication*	*CADFEM GmbH*	*ANSYS Conference & 30. CADFEM Users Meeting*	*24 – 26 October 2012*	*Kassel*	*Scientific Community, Industry*	*900*	*Worldwide*
3	*Press release*	*iwb, TU Muenchen*	*iwb Newsletter 4, 2012*	*Q4/2012*	*Munich*	*Industry, Civil Society*		*Germany, Swiss, Austria*
4	*Press release*	*iwb, TU Muenchen*	*iwb Jahresbericht 2012*	*2012*	*Munich*	*Scientific Community, Industry*		*Germany, Swiss, Austria*
5	*Conference*	*CADFEM GmbH*	*ANSYS Conference & 31. CADFEM Users Meeting*	*19 – 21 June 2013*	*Mannheim*	*Scientific Community, Industry*	*750*	*Worldwide*
4	*Publication*	*CADFEM GmbH*	*ANSYS Conference & 31. CADFEM Users Meeting*	*19 – 21 June 2013*	*Mannheim*	*Scientific Community, Industry*	*750*	*Worldwide*

[4] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[5] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

5	*Conference*	*Deutsche Gesellschaft für Materialkunde e. V.*	*DGM LightMAT 2013*	*3 – 5 September 2013*	*Bremen*	*Scientific Community, Industry*	*238*	*Worldwide*
6	*Conference*	*Fraunhofer IAO*	*8th International Conference on Digital Enterprise Technology - DET 2014.*	*25 – 28 March 2014*	*Stuttgart*	*Scientific Community, Industry*		*Worldwide*
7	*Conference*	*CADFEM GmbH*	*ANSYS Conference & 32. CADFEM Users Meeting*	*4 - 6 June 2014*	*Nuremberg*	*Scientific Community, Industry*	*800*	*Worldwide*
8	*Publication*	*CADFEM GmbH*	*ANSYS Conference & 32. CADFEM Users Meeting*	*4 - 6 June 2014*	*Nuremberg*	*Scientific Community, Industry*	*800*	*Worldwide*
9	*Conference*	*iwb, TU Muenchen*	*19. Augsburger Seminar für additive Fertigung*	*16 June 2015*	*Augsburg*	*Scientific Community, Industry*	*100*	*Germany, Swiss, Austria*
10	*Conference*	*CADFEM GmbH*	*ANSYS Conference & 33. CADFEM Users Meeting*	*24 - 26 June 2015*	*Bremen*	*Scientific Community, Industry*	*850*	*Worldwide*
11	*Publication*	*CADFEM GmbH*	*ANSYS Conference & 33. CADFEM Users Meeting*	*24 - 26 June 2015*	*Bremen*	*Scientific Community, Industry*	*850*	*Worldwide*
12	*Press release*	*iwb, TU Muenchen*	*iwb Newsletter 2, 2015*	*Q2/2015*	*Munich*	*Industry, Civil Society*		*Germany, Swiss, Austria*

13	*Press release*	*iwb, TU Muenchen*	*iwb Jahresbericht 2015*	*2015*	*Munich*	*Scientific Community, Industry*		*Germany, Swiss, Austria*
14	*Publication*		*EU Journal*					

Section B (Confidential[6] or public: confidential information to be marked clearly)
Part B1

The applications for patents, trademarks, registered designs, etc. shall be listed according to the template B1 provided hereafter.

The list should, specify at least one unique identifier e.g. European Patent application reference. For patent applications, only if applicable, contributions to standards should be specified. This table is cumulative, which means that it should always show all applications from the beginning until after the end of the project.

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.

Type of IP Rights[7]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)

[6] Not to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

[7] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2

Please complete the table hereafter:

Type of Exploitable Foreground[8]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[9]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
AeroSim Simulation tool	*In the course of the project, an ANSYS-based simulation tool for the laser beam melting process was developed*	*YES*		*Set of APDL makros*	C25.1.1			
IN718 material data	*The*	*YES*		*Mechanical and thermomechanical material characteristics*	C25.1.1			

[9] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[9] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html