Expanding the Scope and Increasing the Functionality of Digital Twins by Integrating Thermal Simulations

Dorit Kaufmann, Jannis Bojan Weid and Jürgen Rossmann
Institute for Man-Machine Interaction (MMI), RWTH Aachen University,
Ahornstr. 55, 52074 Aachen, Germany

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Abstract: The simulation of components, systems and processes is an established tool in research and development nowadays. When it comes to complex systems and the interaction of components and disciplines, it is crucial to consider all relevant aspects, thus creating a powerful Digital Twin (DT) of a technical asset. In this work, an existing simulation framework for DT will be extended by an interface to Thermal Simulations. The latter one are still widely used as a stand-alone tool due to difficulties on linking the respective models and methods. Thus, the developed approach has its access point in the DT simulation framework and conducts the thermal calculations to an external Finite Element Analysis (FEA) solver by exchanging only characteristic variables. This concept is used as a base for the development of extensions for the DT whose basic functions are the import and preparation of geometric structures for both models, the management of the calculations of the external FEA solver and the visual representation of determined temperature distributions and heat fluxes in the DT.

1 INTRODUCTION

Simulations are a sophisticated and acknowledged way to improve any design process. If single components (and at best complete systems) are depicted computationally, predictions and thus optimisations of the system or process can be made. The more complex the system, the more important interaction gets. Interaction refers to interaction of single components as well as interaction of different disciplines (as mechanics, electrical engineering, material sciences etc.). To enable those interactions, a complete digital model of all relevant aspects of the system is needed, i.e. a Digital Twin (DT).

There are powerful simulation frameworks, where a DT “can live”, i.e. which combine different simulation procedures and thus enable the interaction described above (Schluse *et al.,* 2018). Nevertheless, there are still problems of integrating methods built up on highly discretised models, as it holds true for all sort of Finite Element Analysis (FEA). Apart from the different level of detail of the respective models, especially the computing time for simulation is rather different: DTs usually cover controlling and sometimes further concepts as e.g. hardware-in-the-loop and thus the calculations are performed quite fast; some aspects of the simulation are real-time capable. On the other hand, solving thousands of coupled differential equations for an FEA needs a lot of time to converge and to lead to a reasonable outcome.

One special sector of FEA are Thermal Simulations. They are very important for all mechatronic systems, as movements in general and motors especially always produce heat. It is crucial to know, where this heat is going, i.e. which temperatures can be expected where. Simultaneously, several forms of thermal energy can only be determined in the context of the whole system, e.g. all forms of friction between single components.

In this paper, we present a concept to integrate Thermal Simulations into a DT simulation framework, thus expand their scope and increase their functionality. The concept is based on using an external FEA solver and an automated exchange of characteristic variables. It was implemented successfully and first applications scenarios could be analysed.

The work was conducted as a student project (Weid *et al*., 2021) and is based on our previous work (Kaufmann *et al*., 2017), (Kaufmann *et al*., 2019).

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2 KEY METHODS AND RELATED WORK

When Thermal Simulations are used within DTs to enlarge their functionality, the underlying mathematical and computer scientific concepts of both have to be considered as they form the base of this work. Thus, they shall be briefly described in this section together with an overview of the current state-of-the-art.

2.1 Thermodynamics and Thermal Simulations via Finite Element Analysis (FEA)

Whenever temperature propagation or heat flux is calculated, the general laws of thermodynamics apply. Most important for this paper are the principles concerning thermal conductivity, which describes the propagation of thermal energy due to a temperature difference $\nabla T(\boldsymbol{x})$ in a solid component. A heat flow $\dot{\boldsymbol{q}}(\boldsymbol{x})$ occurs until a homogeneous temperature distribution is achieved. The material of the solid determines how this thermal equilibrium is reached, therefor there is a specific thermal conductivity value $\lambda\ [W/mK]$ for each material, relating both quantities (see Equation 1).

$$\dot{\boldsymbol{q}}(\boldsymbol{x}) = -\lambda \nabla T(\boldsymbol{x}) \qquad (1)$$

This and further equations can be found in much more detail in many textbooks (Baehr et al., 2019). Nevertheless, depending on the complexity of the geometry, material properties and boundary conditions, it becomes impossible to find an analytical solution, so a numerical approach via simulations is required.

Thermal simulations cover a wide spectrum of application areas, as e.g. component development and thermal testing for automotive and aerospace, (Bu *et al.*, 2020), as well as the development of electronic components in general (v.d. Broeck *et al.*, 2017).

Concerning the underlying models and methods of Thermal Simulations, one important distinction has to be made: whether the component of interest is fluent or solid. In the first case, the simulations are performed via Computational Fluid Dynamics (CFD), as it holds true for e.g. the integration of heat exchangers in modern vehicles (Deng *et al.*, 2013). For solids, usually Finite Element Analysis (FEA) is used, as e.g. in the simulation of heat propagation in brake discs (Cho *et al.*, 2008).

In this work, the application scenarios covered by DTs are mostly built around mechatronic systems, where the behaviour of one single component is examined. Thus, only the FEA version of Thermal Simulations is of interest herein.

The thermal impact itself can be physically seen as a load, while the consequences on the component always result in a distribution (of heat/ deformation…). Thus, as it holds true for any FEA, the first step is to mesh the component, i.e. discretize it into several elements connected via a defined set of nodes. The partial differential equations can now be set up element-wise and are coupled. The boundary conditions indicate which outer impacts are acting on the component and are considered in the system of equations as well. This concludes the preprocessing.

Next, the FE model can be transferred to a solver whose task is to obtain the numerical solution of the system of equations. It is always an approximation of the actual values and the quality of the results depends on several factors set during the preprocessing, as the resolution and nature of the meshing, as well as previously defined termination criterions. Due to an exponential relationship between these factors and the computational steps required to solve the equations, an increase in the computational effort beyond a certain point can no longer be compensated by additional computing power, so the calculations take more time. Since the simulation of thermal processes can take several days even for small structures, it is only recommended to carry out the FEA with sufficient experience in order to obtain usable results within a manageable time frame.

In the last step, the determined thermal models are processed for a descriptive presentation. This is the task of postprocessing.

2.2 Digital Twins (DTs)

Simulations are nowadays a recognized standard in many industries, as mechanical or electrical engineering, material sciences, robotics and many more. Simulation methods and algorithms are used throughout the entire development process and lifecycle of a single component or a complete system.

Although each simulation method provides valuable insights separately, there is a lack of a cross-system and cross-discipline approach that also takes into account the interplay of components, environment and disciplines.

A Digital Twin (DT) as a virtual representation of its Real Twin solves this problem, as it considers many (in best case: all relevant) aspects of a complex scenario. Thus, it combines all these simulation domains and the cross-lifecycle use of simulation in a comprehensive concept. At the same time, simulation becomes one of the enabling technologies for DT.

Michael Grieves established the use of the term DT in relation to technical systems in 2002 (Grieves, 2016). In 2010, NASA applied the concept to aerospace and used it to refer to "ultra-realistic simulation" (Shafto *et al*, 2010). Subsequently, the term was illuminated from many sides and got common in various disciplines, e.g. from the perspective of simulations, cyber-physical systems or production engineering.

In 2018, Gartner classified DT as part of the digitized ecosystem as one of the five definitive technological trends and predicted the technology to reach the "productivity plateau" in 5-10 years (Panetta, 2018).

2.3 Coupling of DT and Thermal Simulations

Designing a DT that includes both the thermal behaviour and crucial functions of mechatronic systems (as communication or controlling interfaces) usually leads to a challenge. It emerges from the fact that FEA requires a lot of time for exact results, while simulations of real-time processes such as interaction with other DT or RT (hardware-in-the-loop) shall compute results in the shortest possible time - preferably in real time.

Previous approaches for the realization of an interaction are either rather specific for a certain application (Mussalam *et al*., 2010), (Kral *et al*., 2013) or concentrate on theoretical methods (Busch, 2012). Theoretical approaches are usually based on co-simulation, where quantities are exchanged between subsystems at runtime at specific time intervals (Schmoll, 2015). These subsystems are modelled in a software environment suitable for the respective problem. However, there is no general solution for the handling of the different runtimes and the extrapolation of transferred quantities, what makes an individual consideration necessary (Stettinger *et al*., 2013).

3 CONCEPT

The difficulty of integrating Thermal Simulations into DTs is to link the respective models and methods. Compared to previous work on the integration of Structural Simulations into DTs (Kaufmann *et al.*, 2017), the developed concept follows a similar approach. An external FEA solver performs all Thermal Simulations and the interaction with the DT simulation framework is realised with the exchange of characteristic variables.

3.1 Requirements Analysis

In accordance to previous work (Kaufmann *et al.*, 2017), three main aspects were defined for a thought-out integration of Thermal Simulations into a DT simulation framework:

- Time-efficiency: The interaction only happens at crucial points.
  The usage of the external FEA solver can be switched on/off. A sophisticated choice of critical situations (e.g. when maximum thermal load is expected) saves a lot of computing power and time.
- Validity: The quality of the simulation methods is maintained.
  FEA is a commonly used and well-tested method to perform Thermal Simulations (and further simulations). Using existing meshers and solvers takes advantage of years of development and integrates the huge level of detail into the overall picture of a DT without losing accuracy.
- Usability: The control is done centrally.
  Parameters necessary for the Thermal Simulation are defined in the DT simulation framework. It forms the access point of the integration and thus enables a central control of both simulation methods.

3.2 Workflow: Integrating Thermal Simulations into DT

Following the requirements, a FEA-compatible model containing information about geometry and thermal loads has to be formulated. To achieve maximum efficiency, this is only done for components of the DT, which will experience thermal loads.

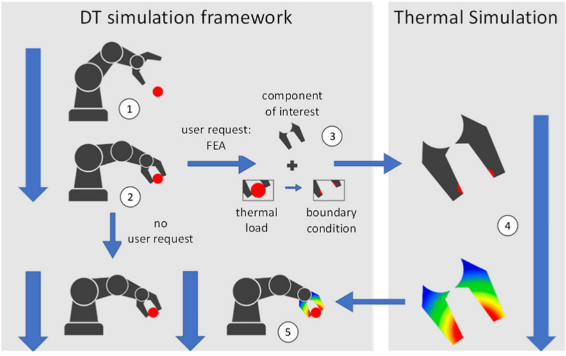

Figure 1: The developed concept enables the integration of thermal impacts into a DT by setting up an automated workflow the user can start if necessary.

A simple application scenario of a robot gripping a sphere illustrates the workflow provided by the concept (see Figure 1). The sphere is hot and the impact on the DT – i.e. the robot – shall be analysed.

The gripping process is simulated in the DT simulation framework (step 1 → 2). As soon as contact is made, the gripper experiences a thermal load. If the user decides a Thermal Simulation is needed, the affected structures – i.e. the gripper jaws – have to be identified and the thermal loads – i.e. hot contact surfaces – have to be converted into boundary conditions (step 3). The prepared model is transferred to the Thermal Simulation software automatically, where the thermodynamics equations are formulated and solved (step 4). The results (e.g. a temperature distribution of the gripping jaws) are returned to the DT simulation framework and thus can be integrated into the original model (step 5). If the user does not request a Thermal Simulation, the simulation continues (i.e. step 5 is reached without any information about the impacts of thermal loads).

4 REALISATION

First of all, the concept could have been realized with any software. Nevertheless, general applicability and usability was considered important and thus suitable programs were chosen for implementation.

4.1 Choice of Software

In this work, the starting point is an existing simulation framework for DT. It already includes many functionalities as dynamics, kinematics, environmental simulation, controlling, sensor simulation etc. (Rast, 2015), (Rossmann *et al*, 2011). It combines the required models, data and simulation methods and integrates them into higher-level processes as well as into real systems (Schluse *et al*, 2018). The abstract "Versatile Simulation Database"-(VSD-) class structure allows to implement special functions in so-called extensions, which can be dynamically added to the program (see Figure 2). Nevertheless, consequences caused by thermal impact cannot be considered yet and thus need to be integrated in the DT simulation framework.

There are many computational tools being able to analyse the effect of thermal impact on components. A thorough analysis of different FEA software was performed before choosing a certain program. The selection criteria were accessibility, usability (i.e. documentation), accuracy, functionality and – of course – compatibility, as an interaction with the DT simulation shall be implemented. Finally, defining an evaluation scheme and distributing points from 1-3 for the different criteria, the open source software Z88Aurora (Z88, 2023) was chosen.

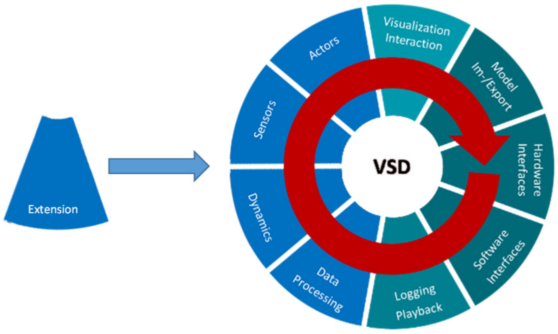

Figure 2: The VSD microkernel structure of the DT simulation framework enables integration of new functionalities via extensions (cf. Rossmann *et al*., 2013).

4.2 Implementation

The exchange of characteristic variables between the DT and the Thermal Simulation is implemented via an interface (see Figure 3). The relevant pieces of information for the respective models are transferred via files (.stl for geometry, .txt for FEA-relevant information and visualization-input). The files have the syntax the Thermal Simulation software Z88Aurora requires. The generation and processing of the files (i.e. the interface) is controlled by the DT simulation framework. Two extensions were implemented that integrate the new functionalities:

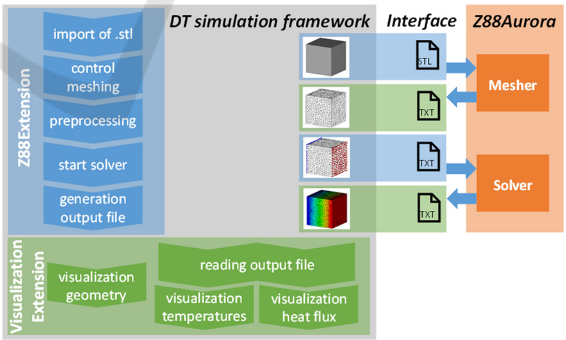

Figure 3: Design of the interface. The exchange of characteristic variables is done with files (middle), which contain the information for the mesher and solver of the Thermal Simulation software Z88Aurora (right). The interface is controlled by two extensions of the DT simulation framework. One handles the communication to the Thermal Simulation (i.e. the preprocessing; corresponding functions marked in blue), the other one the communication from the Thermal Simulation (i.e. the visualizations; corresponding functions marked in green).

- Z88Extension handles all communication from the DT to the Thermal Simulation. Besides the infrastructure for the geometry import via an (possibly external generated) .stl-file, this consists mainly of the preprocessing for the FEA (i.e. meshing control, definition of boundary conditions, start of the solver, generation of output files). Z88Extension has its own GUI element in the DT simulation framework, where the user can set all relevant parameters.
- VisualizationExtension handles all communication from the Thermal Simulation to the DT. This means in specific the processing of the output files, i.e. the visualization of the results from the Thermal Simulation.

5 EXEMPLARY USE CASE: THERMAL SIMULATION OF THE DT "VEHICLE AXLE"

In the following, the functions of the interface are described on the basis of a thermal analysis of the geometry shown in Figure 4 which can be interpreted as a highly simplified version of a vehicle axle.

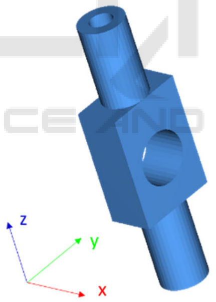

Figure 4: The imported geometry as base for the DT "vehicle axle".

This use case is only exemplary and shall emphasize the functionality of the developed integration of Thermal Simulations into a DT rather than optimizing a real component. Thus, the object size is rather small to keep the required computational power low and thermal conductivity coefficients were chosen, such that temperature differences and heat flux could be particularly well illustrated. Nevertheless, the structure contains subcomponents, which are also used in the modeling of more complex structures (cylinders, hollow cylinders, cuboids, cavities). Furthermore, there is a certain reference to real application scenarios: operation of a vehicle generates heat due to friction of rotating shafts or running gears, which then propagates along the axis.

5.1 Geometry Import and Meshing

The geometry is imported into the DT simulation framework and thus the DT "vehicle axle" is created. The geometry comes as an .stl file, which was created externally with the help of CAD-software, following the standard design process in mechanical engineering.

First, the required density of the mesh has to be defined. This can be easily done in the GUI of the DT simulation framework by choosing different inputs for the respective parameter in the Z88Extension. Figure 5 shows the results for varying the parameter, i.e. generating a finer mesh. The meshing of Figure 5 c) was taken for the following analyses, since the FEA nodes are close enough to each other to map temperature distributions and heat flux with a high spatial resolution.

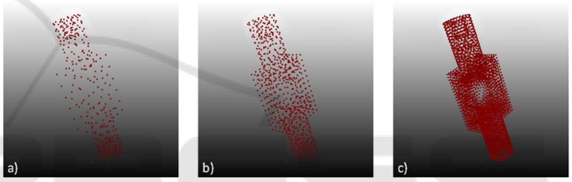

Figure 5: Nodes of the mesh for different values of the respective parameter in the Z88Extension, which controls the mesher from Z88Aurora out of the DT simulation framework.

5.2 Temperature Analysis

First, simple temperature distributions are simulated in the DT of the vehicle axle. Thus, specific temperatures on the end faces of the axle are defined via the DT simulation framework as boundary conditions for the FEA. The GUI element of Z88Extension provides the respective input options. The upper boundary surface along the z-axis is assigned a temperature of $T_1 = 100°C$, the lower boundary surface a temperature of $T_2 = 0°C$. Figure 6 a)-c) shows the resulting temperature distributions for different thermal conductivity coefficients λ_i.

The increasing propagation of temperature within the component resulting from an increasing thermal conductivity coefficient can be easily seen. The temperature variation is typical for this set of boundary conditions and resembles the results of other scientific publications (Prabhu *et al.*, 2018).

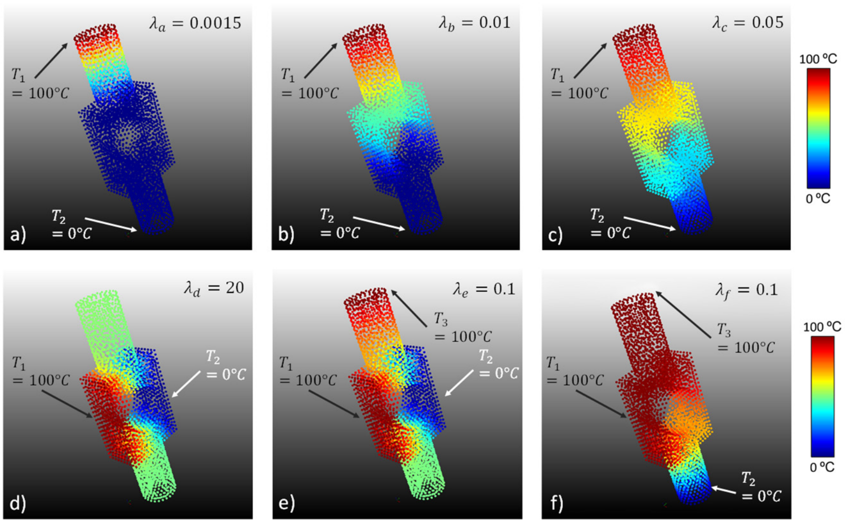

Figure 6: Temperature distributions of the DT are calculated for different boundary conditions (temperatures T_i on different surfaces) and different thermal conductivities λ_i.The upper row shows a typical temperature shift for increasing λ. The lower row shows mostly asymmetrical and thus more complex boundary conditions.

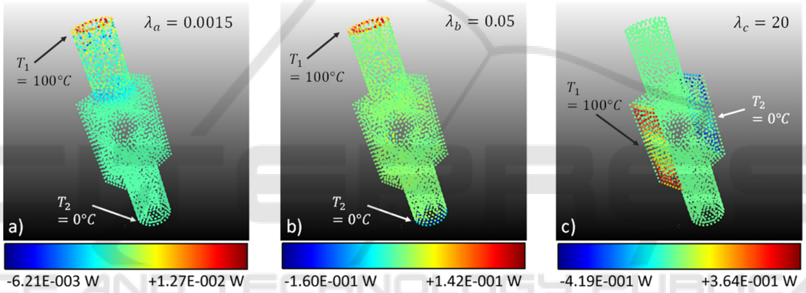

Figure 7: Heat flux in the DT for different boundary conditions (temperatures T_i on different surfaces) and different thermal conductivities λ_i.

In a second step, more complex boundary conditions were applied, i.e. also other faces of the axle got a defined temperature value as an input (see Figure 6 d)-f)). While d) shows again a straight temperature drop along the y-axis due to symmetrical boundary conditions, the axle was exposed to asymmetrical boundary conditions in e) and f). Nevertheless, the resulting temperature distributions are still reasonable (e.g. the similar temperature of the connection between the upper cylinder and the cuboid in e)).

In a last step, the temperature distributions were calculated in a “pure FEA” in Z88 without the DT simulation framework. The results were the same in both cases.

5.3 Heat Flux Analysis

For an exemplary analysis of heat flux, the boundary conditions of the temperature analyses were taken. In Figure 7, the colours code for the heat flux balances of the nodes. In the following, we define a positive heat flux balance such that the amount of outgoing heat fluxes exceeds the amount of incoming heat fluxes. Figure 7 a) shows the heat flux balances of the boundary conditions from Figure 6 a). The colour gradient illustrates that changes only occur in the upper cylindrical subbody. Due to the constant temperature in the lower part of the axle, this was expected. Figure 7 b) shows the heat flux distribution corresponding to Figure 6 c). In contrast to the previous heat flux distribution, the temperature changes now also reach the lower face of the lower cylindrical subelement, so there occur negative heat flux balances. Figure 7 c) shows the heat flux distribution of the temperature distribution shown in Figure 6 d). A constant heat flux balance is again established inside the body, but is no longer constant on the boundary surfaces. This can be explained by the cavity in the centre of the body, where no thermal conductivity was specified, thus acting as an ideal insulator.

5.4 Discussion

The first example of a DT with integrated Thermal Simulations was created, examined and thermodynamically analysed from within the DT simulation framework.

Thus, the requirements of usability and enhancement of time-management were met; both secured by a central point of access for the whole interaction with the FEA in the DT simulation framework.

Besides, the resulting temperature distributions and heat fluxes were the same in the DT simulation framework as in a "pure FEA" only using the Thermal Simulation software, which validates the interface and the approach. Furthermore, they showed the expected physical behaviour in accordance with other Thermal Simulation related publications. Thus, also the required preservation of quality of each simulation method respectively was validated.

6 CONCLUSION

The aim of this work was the integration of Thermal Simulations via FEA into an existing DT simulation framework and thus expanding the scope of DTs.

In the development of the concept for this integration, a special focus was set on the general usability and validity. Thus, the DT environment served as access point to conduct Thermal Simulations of defined components. This concept also optimizes time management, as this can be done when critical situations occur in the application scenario (contrary to performing an FEA at every time step).

For the specific implementation, new extensions for DTs were developed, which manage the externally performed Thermal Simulations with Z88Aurora. During the implementation, it was necessary to convert the DT model to a model that is FEA compatible. This was achieved by importing the geometries from external .stl files. The transformation of the models and the entire setup of the Thermal Simulation was automated such that a high degree of user-friendliness can be guaranteed. The extensions currently include the calculation of steady-state temperature and heat flux distributions, where the starting point is a temperature distribution on the surface.

7 OUTLOOK

Although a first approach of integration of Thermal Simulations into a DT was successfully performed, there are still opportunities for future work. For example, more complex concepts concerning thermodynamics could be integrated (e.g. thermal loads due to thermal radiation, convection or electric currents). In addition, the thermal processes might result in geometric changes that have been neglected so far. Thus, a combination with the structural simulation framework for DT (Kaufmann *et al.,* 2018), (Kaufmann *et al.,* 2019) will be interesting. The same holds true for a specific application scenario in space robotics, where heat influx is already calculated in a DT, but not connected to FEA (Rossmann *et al.,* 2018).

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