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Developing a Thermal Design Optimization Method Based on the Model of SGE - System Generation Engineering

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Abstract: Electro-hydrostatic actuators are complex systems used in aircraft of future generations. Their development requires state of the art simulation and design methods to increase their efficiency. We analyzed the development of a design optimization method with the model of SGE – System generation engineering. We identified key points during development that lead to a high risk and therefore a required high effort. We conclude that the model of SGE is able to identify risks during the development of complex design methods. This risk assessment provides a benefit when planning future generations of design methods. Further, the model of SGE creates a graspable description of the development process.

Keywords: System Generation Engineering, Electro-Hydrostatic Actuator, Design Optimization Method

1 Introduction

The greenhouse gas emissions of aviation make up only a relatively small part of the total emissions, but they are expected to increase the most in the upcoming years (European Environment Agency, 2023). Even though current research indicates a shift towards alternative propulsion systems such as hydrogen-based propulsion (Fuel Cells and Hydrogen 2 Joint Undertaking, 2020) or electric propulsion (Wolleswinkel et al., 2024), long-range aircraft will rely on hydrocarbons for the near future (Ansell, 2023). It is therefore necessary, to optimize existing aircraft to reduce their carbon footprint. One method to reduce the carbon emissions of an aircraft is the concept of the so-called More-Electric-Aircraft (MEA) (Sarlioglu and Morris, 2015). A central part of the MEA is to replace hydraulic power distribution within the aircraft by electric power distribution in new system generations. This requires the use of an Electro-Hydrostatic Actuator (EHA) instead of a conventional hydraulic actuator to move control surfaces. An EHA is a highly complex system compared to conventional hydraulic actuators (see Figure 1). These EHAs are subject to a continuous development to further increase their efficiency.

Figure 1. Comparison of an EHA (left) and a conventional hydraulic actuator (right) as integrated into the wing for aileron actuation (Van Den Bossche, 2006)

Besides the improvement of the system itself, the simulation methods and design approaches are also subject to a continuous development. Analogous to the product development, the development of a simulation method is not started from scratch. Existing parts of simulation methods serve as the reference for the development of a new generation. The model of SGE – System Generation Engineering according to Albers enables a description of the development of products and systems based on references (Albers and Rapp, 2022). An EHA is a complex system that requires intricate, multidisciplinary design methods (Li et al., 2014). According to Albers, these methods can as well be developed based on references and in generations.

The aim of this work is to show the creation of a simulation-based design method with the help of the model of SGE. We demonstrate how the model of SGE can be used to identify possible risks during development of the method. Furthermore, the description based on the model of SGE can help with identifying and communicating the challenges and intermediate steps of the method.

In Chapter 2 we give a short introduction to the theoretical background of both simulation methods and SGE. In chapter 3 we describe the different steps of the proposed design method in the context of SGE. In chapter 4 we show how the model of SGE was able to predict the risks during the implementation of certain changes.

2 Theoretical background

Conjugate Heat Transfer (CHT) simulations are an established tool in product design (Murthy and Mathur, 2012). It combines Computational Fluid Dynamics (CFD) and heat transfer in solids to efficiently calculate the temperature distribution within a system by incorporating all types of heat transfer i.e., conductive heat transfer, convective heat transfer and radiative heat transfer, while the latter is often neglected.

This research was conducted on an industrial EHA (BAS.50/32.U04.201.200 MI.BA100.G2.P42, AHP Merkle GmbH, Gottenheim, Germany). Figure 2 shows the EHA and an exemplary simulation result for the temperature distribution resulting from a defined load case. For the setup of the simulations in this work, certain model assumptions and boundary conditions were made:

- The heat of the EHA is not dissipated by forced convection but rather natural convection to enable an accurate validation with test bench measurements.
- Due to the different time scales of heat transfer in solids and fluid movement, we modelled the periodic movement with steady-state simulations. The geometric movement of the EHA is neglected.
- Except for internal hydraulics, the material is modelled as solid material.
- The generated heat from motor and pump enters the system through separate volumetric heat sources.

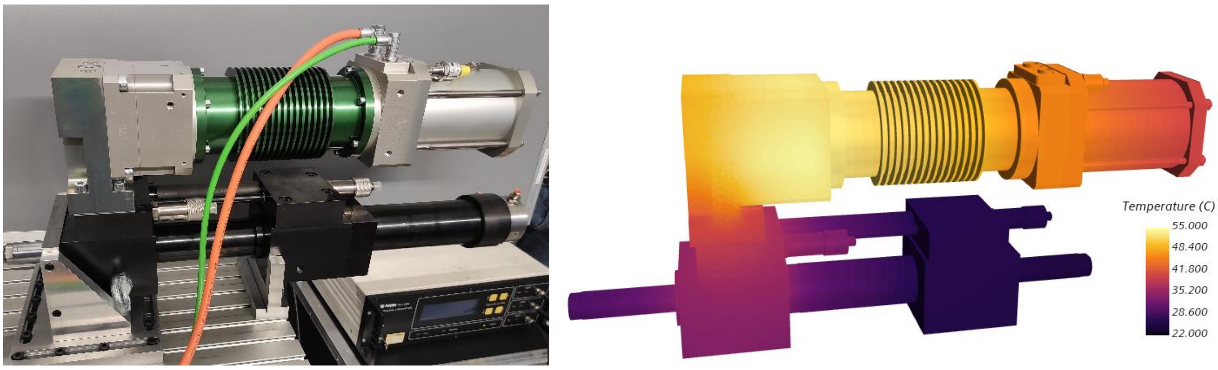

Figure 2. Industrial EHA set up on test bench (left) and temperature distribution from the simulation (right)

The method of topology optimization originates from the optimization of mechanically loaded structures to reduce their weight (Bendsøe and Kikuchi, 1988). The core concept of topology optimization is to distribute material within a given design space under certain restrictions to minimize a predefined objective function. This is an iterative process which requires solving a possibly large simulation model in each iteration. It has since evolved to accommodate for the high computational cost required, and can now be applied to larger structural problems as well (Mukherjee et al., 2021). Besides structural optimization, topology optimization can also be applied to thermal problems (Dbouk, 2017). The computational cost of thermo-fluid problems, particularly transient CHT problems, is even larger, which hinders the use of topology optimization. In previous works, we proposed models and methods which reduce the computational cost to enable the use of topology optimization for the thermal optimization of large systems (Knecht et al., 2023; Knecht and Albers, 2022).

Development of Simulation Models

The aim of a simulation model is to virtually reproduce a real-world problem with a defined degree of accuracy while deliberately omitting certain aspects or phenomena (Stachowiak, 1973). The task of a simulation engineer is to decide, which aspects or phenomena to consider in the simulation model, and which to omit. Theories of simulation model development were formulated as early as 1984 (Nance, 1984). Based on this work, a systematic methodology how to develop simulation models, the “Conical Methodology”, was proposed (Nance, 1994). While the main principles still apply for simulation model development in this day and age, advances in hard- and software as well as new numerical methods changed how simulation models are developed. More recent literature describes modern simulation model development in detail, noting that the process of simulation model development should be adequately planned (Aumann, 2007; Robinson, 2014)

There are several case studies that describe simulation model development for specific problems, such as simulation models for a digital twin in historical buildings (Angjeliu et al., 2020), simulations to model production processes (Rosova et al., 2022) or simulations to predict the spread of viral infections (Tkachenko et al., 2021). They all developed a simulation model from scratch, without utilizing simulation model reuse, which can potentially reduce the effort required to develop a simulation model.

Simulation models can be reused for different applications. (Hussain et al., 2022) offer a holistic review on simulation model reuse in systems design. This simulation model reuse is based on several steps: “Model Search”, “Model and Model Component Selection”, “Model Components Composition”, “Model Adaption”, “Model Validation, Verification, and Accreditation”, and “Model Simulation”. Systems design simulation models differ from CHT simulation models as used in this work, however, the “Model Adaption”-step can be applied in this case as well. (Robinson et al., 2004) offer a more general view on simulation model reuse. They state that one problem is that there is little motivation to create reusable models, since other people benefit from the effort. This does not apply in our case, since we developed our models to be reused by ourselves.

Engineering based on references – Model of SGE – System generation Engineering

Contrary to the presented simulation model development and reuse in the literature, we apply the model of SGE – System-Generation-Engineering to this case study of iterative simulation model development.

Each development is based on previously known elements. The model of SGE – System-Generation-Engineering according to Albers provides an approach that describes the fundamental phenomena in the evolution of new products and systems. The model is based on two main hypotheses (Albers et al., 2015; Albers and Rapp, 2022):

- Every development is based on a reference system. The reference system for the development of a new system generation is composed of elements of already existing or planned socio-technical systems. The reference system represents the basis for the development of the new system generation (Albers et al., 2019b).
- A new system generation is developed based on the reference system through a combination of three types of variation: principle variation (PV), attribute variation (AV) and carryover variation (CV) (Albers et al., 2020).

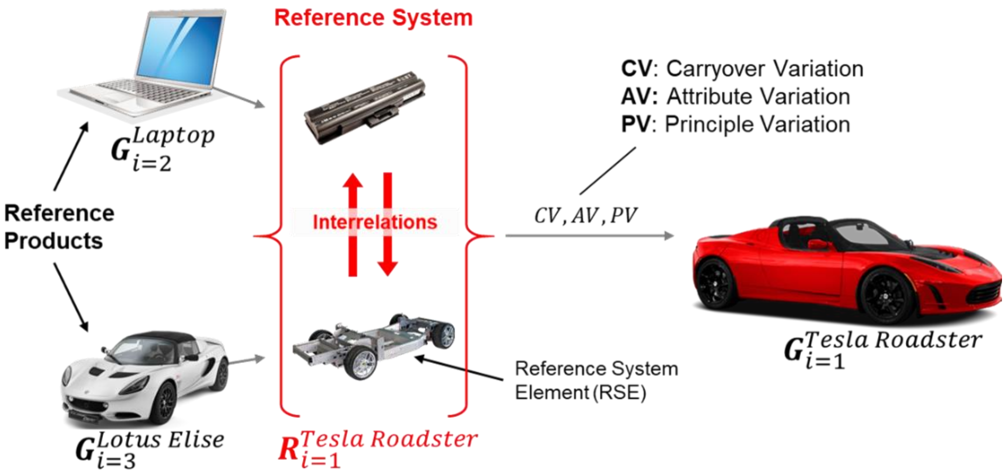

Figure 3. All new systems are developed using a reference system that incorporates existing socio-technical elements and by combining these elements through different variations, modified based on (Albers et al., 2019b). The reference products, in this case a laptop and a sports car, together comprise the reference system. From this reference system, different elements are combined and varied to form a new product generation, in this case an electric sports car.

The model with which elements from the reference system $\boldsymbol{R}_{i=n}$ are transferred to a new generation can be expressed using the formula below. If the system is currently under development, the index $i = n$ is set. Future generations in development are given an ascending index $\boldsymbol{G}_{i=n+1}$. Previous generations are given a descending index $\boldsymbol{G}_{i=n-1}$, which is therefore the current generation on the market.

$$\boldsymbol{R}_{i=n} \rightarrow \boldsymbol{G}_{i=n} = \text{Ü}\mathbf{V}_{i=n} \cup \mathbf{AV}_{i=n} \cup \mathbf{PV}_{i=n}$$

With an increasing share of AV and PV (together they form the new development share), the risk and effort involved in developing the system also tends to increase. The origin of the reference system elements also plays a role in the risk. If they come from the same company and have already been handled by the developer, the familiarity lowers the risk, compared to the case where these elements come from another company, another industry or even from research. Figure 4 shows a graphical representation of this development risk portfolio. The risk portfolio can be used to make initial statements and estimates about the expected development risk and the cost of the planned development at an early stage, even before the development activity is carried out (Albers et al., 2017a). We discuss the risk portfolio applied to our development in chapter 4.

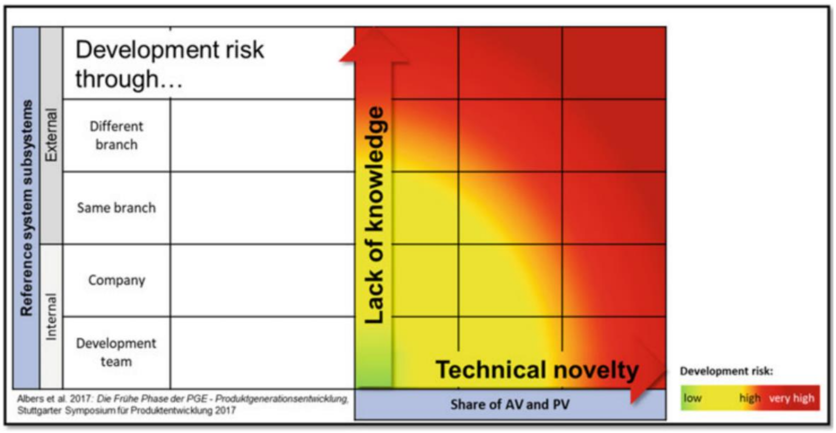

Figure 4. Development risk portfolio based on the reference system and variations to evaluate system in an early phase (Albers and Rapp, 2022)

Not all developments immediately result in a new system generation that can be placed on the market. Various intermediate stages on the way to the development of a new system generation are described as engineering generations in the model of SGE. An engineering generation in itself is a completed system. It has its own system of objectives, which can differ from the system of objectives of the superior system generation. Therefore, even though it doesn't satisfy the original system of objectives, it can still serve as a reference system element for other systems.

In the following chapter we will describe the different engineering generations that resulted in the new system generation of the design method.

3 Iterative development of the design method

The overall aim is a design method to create thermally optimized designs for an EHA, which makes use of the method of topology optimization to create a design with an optimized temperature distribution within the system. This is the general system of objectives. The development of the design method was an iterative process. Within each step, adjustments and/or additions were made to further specify the system of objects. This iterative development with clearly defined intermediate stages lends itself to being described retrospectively using the model of SGE. Since the topology optimization requires an underlying simulation model, the intermediate aim was to create a CHT simulation model of an EHA that accurately predicts the temperature distribution. This intermediate aim forms the system of objectives for engineering generations towards the final system generation.

The proposed design method consists of different building blocks that are linked together, therefore we make use of the coupling framework described in (Albers et al., 2022, 2017b) for the graphical representation of different generations and their variations. Within this coupling framework, each building block i.e., part of the simulation/design method is a separate module. The level of detail is defined by the product developer based on different requirements of the intended use case. In our case, we chose a relatively low level of detail to ensure an easy communication while still maintain the needed complexity to describe the changes from generation to generation. Each module consists of the used method, the used tool and a model-specific description. The modules are interconnected and exchange information labeled as a parameter set $\mathbf{P}_x$. The virtual system is connected to the environment through interfaces.

An extension of the coupling framework as presented in (Albers et al., 2022) enables the use of variation operators from the model of SGE – system generation engineering. In the context of coupled simulation methods, these variation operators are defined as follows (Albers et al., 2020): A carryover variation keeps the element of the reference system the same, as well as the linkage between connected modules. An attribute variation requires changes in the attribute of the reference system element, but the linkage between connected modules remains the same. A principle variation allows for changes to the reference system element's attributes but also comes with necessary adaptions to the linkage of different modules, comparing the reference system element and the implementation in the current system generation under development. The type of variation operator is depicted in modules that were changed, which in turn are highlighted.

3.1 Engineering generation 1: Simple simulation method

The first engineering generation was simple CHT-simulation model created in the software Siemens Simcenter Star-CCM+. The system of objectives comprises a simulation model to accurately predict the temperature distribution, preferably with low computational cost. Therefore, only the essential mechanisms such as convective and conductive heat transfer were included. Internal fluid flow of the hydraulic fluid was neglected. The reference system in this case comprises purely elements from the state of the art as e.g., the geometry description through a CAD model, created in this case in PTC Creo, and the CHT simulation method. Figure 5 shows a graphical representation of the first engineering generation.

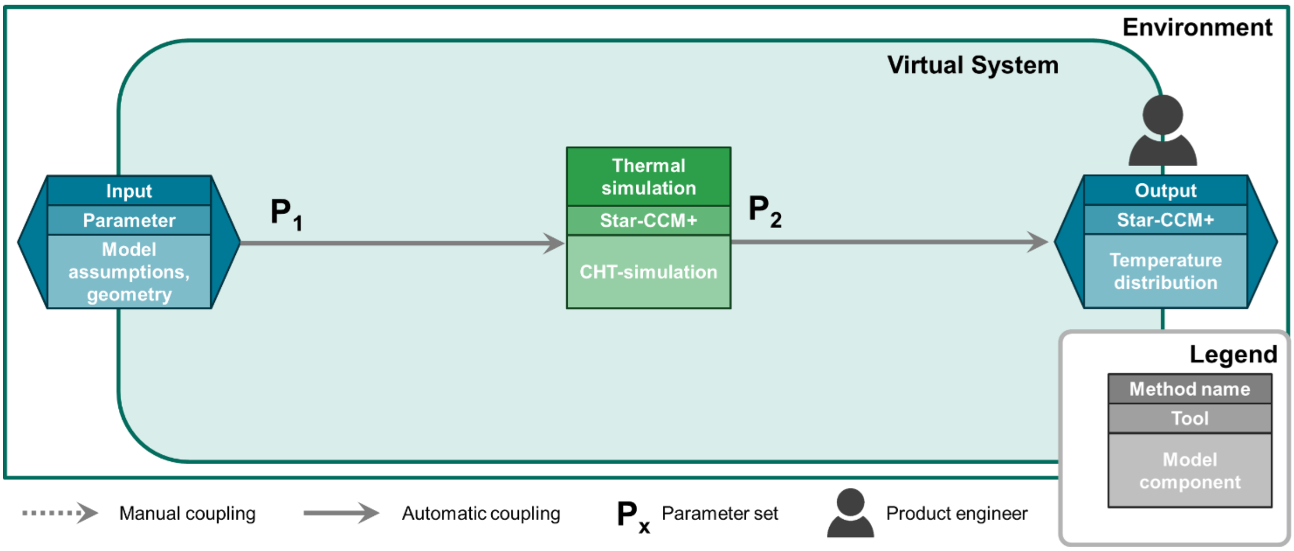

Figure 5. Graphical representation of the first engineering generation $\boldsymbol{E}_{n,1}$ of the simulation method according to (Albers et al., 2022)

The resulting temperature distribution of the CHT-simulation in $\boldsymbol{E}_{n,1}$ is a finished step in itself, of which conclusions for further design iterations can be drawn. Comparison of the temperature distribution with test bench results showed however, that the error due to model assumptions is relatively large. This engineering generation can still serve as a reference system element for a different system, where an accurate temperature prediction is of less importance. The superior system of objectives (i.e., the design method based on the method of topology optimization) however requires an accurate prediction of the temperature. This indicates that even though the engineering generation $\boldsymbol{E}_{n,1}$ works and produces results of a certain quality, further improvements are necessary.

3.2 Engineering generation 2: Extension by radiative heat transfer

Investigations during the validation of the first engineering generation showed, that radiative heat transfer has a relevant influence on the simulation result. The resulting temperature distribution from engineering generation 1 predicted an overall higher temperature than measured on the test bench. We therefore included radiative heat transfer in the simulation model. The adaption resulted in the second engineering generation.

The reference system for $\boldsymbol{E}_{n,2}$ consists of the CHT-simulation model and a radiation simulation model. The CHT-simulation was taken as a carryover variation from $\boldsymbol{E}_{n,1}$. The radiation simulation model coming from the state of the art (Sheremet, 2021). The two parameter sets, namely input and output of the thermal simulation remained unchanged. Therefore, this change is classified as a carryover variation. Since no attribute or principle variation is applied, the development share of AV and PV technically equals zero. This, however, does not necessarily indicate an absence of risk during the development. The risk will be very low, though, since the model of radiative heat transfer is an established simulation model in the state of the art.

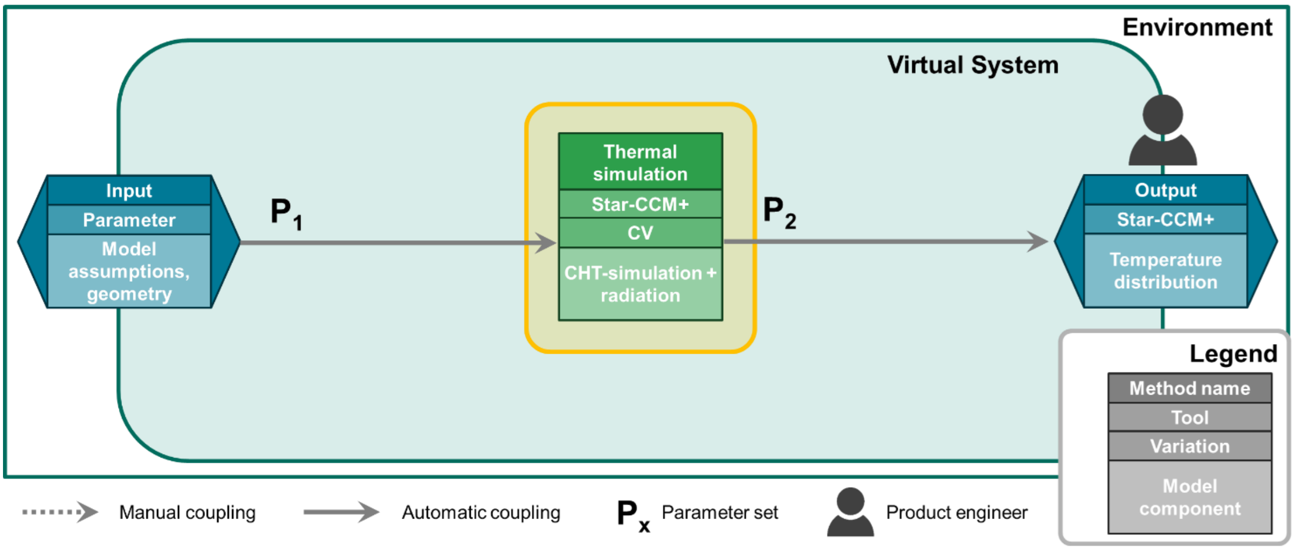

Figure 6. Graphical representation of the second engineering generation $\boldsymbol{E}_{n,2}$ of the simulation method

The temperature distribution resulting from the extended simulation model was again validated with test bench measurements. The overall error between simulation result and measurements was lowered. However, for the regions around the heat sources, specifically the hydraulic pump, the temperature prediction was too high. One reason for this could be, that the internal movement of hydraulic fluid was not considered until now. This movement distributes heat throughout the EHA and flattens the temperature distribution. In order to account for the convective heat transfer by the motion of the hydraulic fluid, we came up with a surrogate model to replicate the averaged transient temperature distribution in a steady-state simulation (Knecht et al., 2023).

3.3 Engineering generation 3: Extension by surrogate model

The reference system for $\boldsymbol{E}_{n,3}$ comprises the simulation model from $\boldsymbol{E}_{n,2}$, and the surrogate model from (Knecht et al., 2023). This surrogate model is a parametric optimization, which takes the same parameter set as the thermal simulation itself as an input. The output parameter set is a combination of thermal conductivities that are applied to the thermal simulation. The thermal simulation model itself remained unchanged and is therefore a carryover variation. The surrogate model was originally developed for an oscillating flow in a straight pipe. In order to apply it to an EHA, it had to be adapted to account for differing geometries. It is therefore classified as an attribute variation. Hence, it comes with an increased risk during development. This increased risk became apparent in the required effort needed to adapt the surrogate model.

Figure 7 shows the graphical representation of $\boldsymbol{E}_{n,3}$. As mentioned before, the input of the thermal simulation model remained unchanged. Parameter set $\mathbf{P}_2$ is added for visualization purpose only. It is a subset of $\mathbf{P}_1$ from $\boldsymbol{E}_{n,2}$.

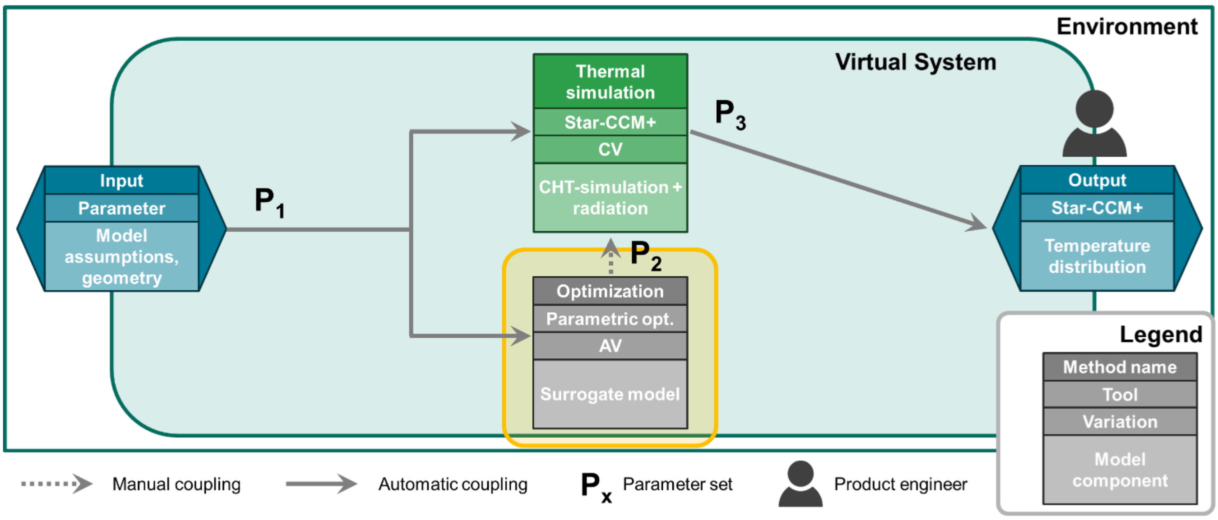

Figure 7. Graphical representation of the third engineering generation $\boldsymbol{E}_{n,3}$ of the simulation method

3.4 Engineering generation 4 / Generation n: Addition of topology optimization

The overall system of objectives of the proposed design method was to incorporate topology optimization into product development of thermally stressed systems. As described in chapter 2, the origin of topology optimization is in structural mechanics, where it is nowadays an established tool. It has already been used in the design of heat exchangers. However, these applications considered mostly a small problem size or simplified problem formulations. This means, that adaptions to the topology optimization method needed to be done when integrating it into the design method.

The method of topology optimization is considered as an external reference system element and is therefore connected with a high risk when integrating it into the coupled method. The high risk manifested in a large effort necessary to adapt the topology optimization to large scale thermal problems. The invested effort resulted in the research result of the so-called two-step topology optimization presented in (Knecht and Albers, 2022). The adapted method of topology optimization is classified as a principle variation coming from the state of research. The other reference system elements were the thermal simulation model, and a CAD-environment, such as PTC Creo, for the necessary post-processing of the optimization result (Subedi et al., 2020). The thermal simulation model in conjunction with the surrogate model is a carryover variation from the preceding generation. The CAD-environment is also a carryover variation coming from the state of the art.

Up until the preceding generation, the system of objectives for the engineering generations was an accurate prediction of the temperature distribution within the EHA. For them to be useful in product development, the product engineer had to interpretate the results and manually derive design changes from it. In this generation, the outcome is directly a new system design created with the method of topology optimization. This satisfies the original system of objectives. Therefore, this engineering generation $\boldsymbol{E}_{n,4}$ is equally $\boldsymbol{G}_{i=n}$.

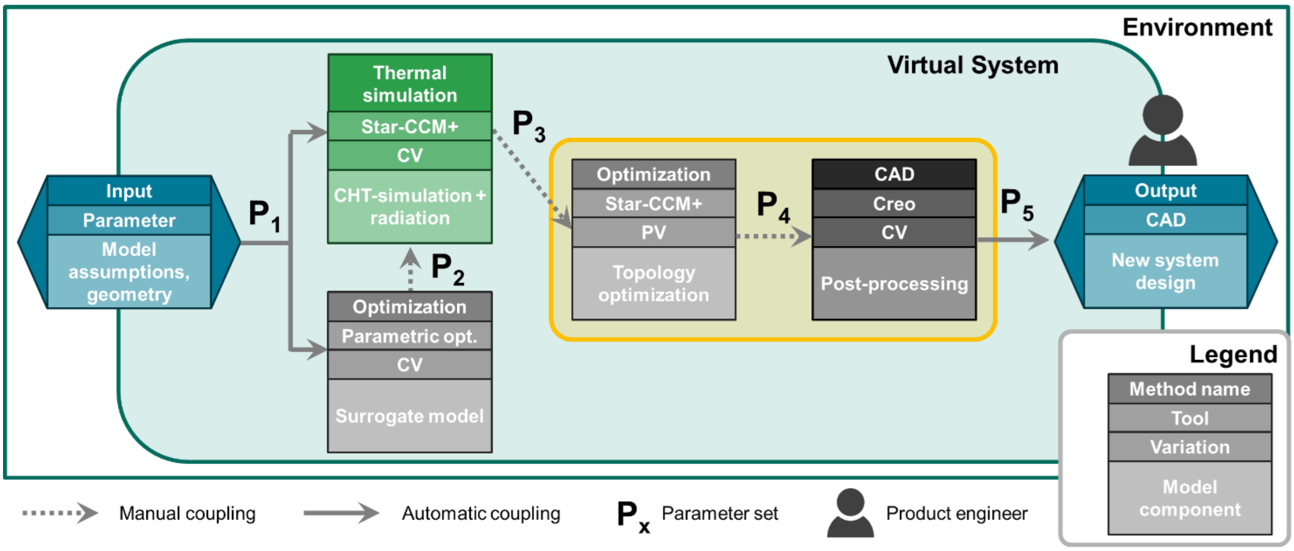

Figure 8. Graphical representation of the fourth engineering generation $\boldsymbol{E}_4$ of the simulation method which is equally the first generation $\boldsymbol{G}_{i=1}$ of the design method, adapted from (Knecht and Albers, 2024)

The proposed method combining the surrogate model and topology optimization as shown in Figure 8 enables the generation of thermally optimized designs, taking the internal heat transfer by the hydraulic fluid into consideration. Figure 9 shows a graphical representation of the development process for the proposed design method, where the interactions between system generation, engineering generations and their variations, and the system of objectives can be seen.

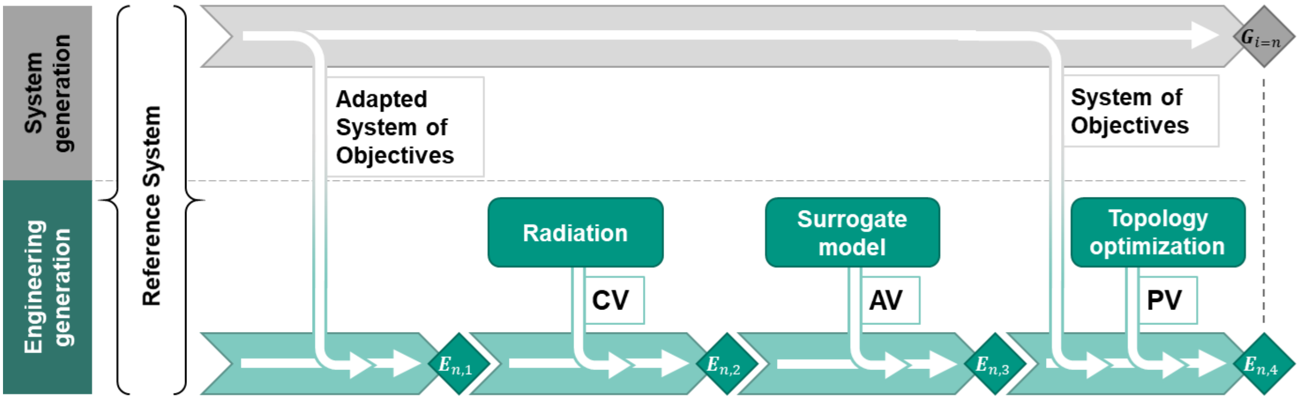

Figure 9. Graphical summary of the development process for the design method and its engineering generations, adapted from (Albers et al., 2019a)

By using the model of SGE to describe the development of the design method, we are able to identify possible risks during the development. After identifying these risks, the future development can be planned more efficiently by allocating resources according to the estimated effort. Changes with a high risk likely need more time to implement compared to changes with a low risk. Furthermore, the description of variations between different (engineering) generations enables an easy communication on a high level towards stakeholders. Each (engineering) generation is a finished step in the development process, where the integrated changes from the preceding generation and planned changes for the upcoming generation can be stated. The latter can be additionally provided with an estimated risk in development.

Not all system generations have a preceding generation, though. The proposed design method has the characteristics of a $\boldsymbol{G}_{i=1}$-generation. This means that there was no immediately preceding design method that could be adapted or extended. The method was constructed of elements from the reference system, which themselves describe parts of the overall functionality. The reference system in this case comprises different elements of both the state of the art and current research.

4 Risk portfolio

The changes between each generation of the coupled method can be correlated to a risk. This risk indicates the development risk of an unforeseen increase in effort and/or time needed to incorporate the changes. The risk does in this case not refer to inaccurate simulation results or erroneous modelling, but solely to the required effort when implementing changes from one simulation model generation to the next. The risk depends on the new development share and the type of variation e.g., carryover, attribute or principle variation, where a carryover variation comes usually with the smallest risk and a principle variation with the possibly highest risk.

Figure 10 shows the risk portfolio as introduced in (Albers et al., 2017a) and described in chapter 2 applied to the development of the simulation/design method from chapter 3.

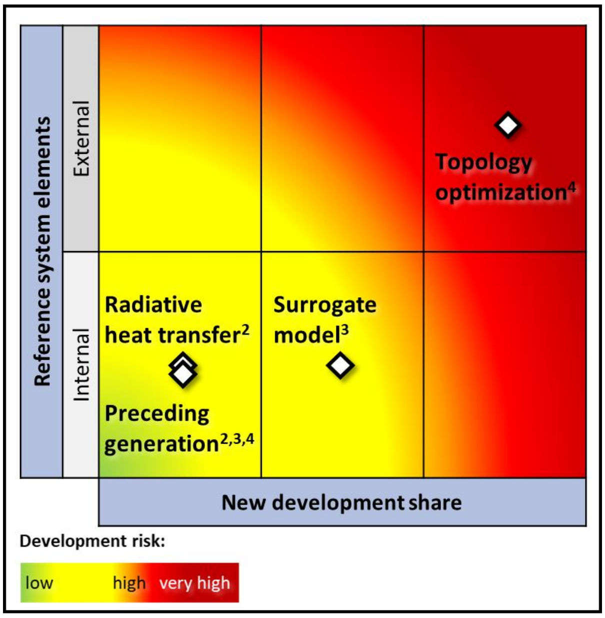

Figure 10. Risk portfolio of the coupled simulation/design method, containing the different reference system elements that were combined in each generation according to (Albers et al., 2017a)

The diamonds depict the reference system elements that were used throughout the generational development. The reference system element *Preceding generation* is depicted only once, but for each use it constitutes the preceding generation, respectively. The other reference system elements were placed according to their share of AV and PV and their origin. The superscripts denote the engineering generation in which the elements were used.

It becomes apparent, that engineering generation 3 came with a higher risk and engineering generation 4 with the highest risk. Both required an increased effort in their implementation. This effort resulted in the aforementioned research works (Knecht et al., 2023) and (Knecht and Albers, 2022).

5 Conclusion

We retrospectively investigated the development of a design optimization method in the context of the model of SGE – System Generation Engineering. We were able to identify possible risks when incorporating reference system elements that were either external or had a higher new development share. These risks manifested in a high effort during the implementation of the changes.

Although this work was done in hindsight, it shows that the model of SGE is suitable for the application to the development of simulation and design methods. By analyzing planned changes or adaptions to a simulation model, SGE can identify possible risks during development. This is especially true for iterative simulation model development, where model reuse and adaption occur. The description through the model of SGE further enables a clear communication of the development process. Planned changes as well as intermediate stages (engineering generations) and their objectives can be explained very well.

For future works or applications of the model of SGE to the development of simulation and design methods, the risk assessment can be taken into account already during the development process. Proposed changes or additions need a careful investigation and can then be classified according to the expected risk and/or effort of their implementation. This can then be used when planning resources accordingly. Furthermore, the graspable description of complex methods and planned changes through the model of SGE can help the engineer when communicating a requested adaption or extension of a simulation/design method.

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