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System Elements Identification Method for Heat Transfer Modelling in MBSE

Patrick Jagla *, Georg Jacobs, Vincent Derpa, Lukas Irnich, Gregor Höpfner, Stefan Wischmann and Joerg Berroth

Institute for Machine Elements and Systems Engineering, Eilfschornsteinstraße 18, 52062 Aachen, Germany; georg.jacobs@imse.rwth-aachen.de (G.J.); vincent.derpa@imse.rwth-aachen.de (V.D.); lukas.irnich@imse.rwth-aachen.de (L.I.); gregor.hoepfner@imse.rwth-aachen.de (G.H.); stefan.wischmann@imse.rwth-aachen.de (S.W.); joerg.berroth@imse.rwth-aachen.de (J.B.)
* Correspondence: patrick.jagla@imse.rwth-aachen.de

Abstract: Today's systems are becoming increasingly complex due to the multitude of interactions between subsystems. This is also true for the electromechanical drivetrain and its physically interacting cooling system. In order to provide a virtual representation of such systems, including system architecture and product behaviour, model-based systems engineering (MBSE) introduces system models. System models are built using system elements and reoccurring models. MBSE, therefore, enhances the efficient development of complex systems by promoting model reuse in interdisciplinary architectural modelling. The reuse of models, such as calculation models, reduces redundancy, accelerates development iterations, and streamlines consistency. However, there is a lack of standardised and reusable model libraries to facilitate this reuse. In the approach in this paper, the reusability of those models is facilitated by the system elements, referred to as "solution elements". MBSE system elements enable the structuring, reuse, and organization of models within model libraries. The identification of these system elements for heat-exchanging systems, however, remains an open challenge. Consequently, the aim of this paper is to develop a method for systematically identifying system elements in heat-exchanging systems, providing a formalized approach to reusing thermal models. The method focuses on functional and heat-transfer processes at the contact level referred to here as thermal contacts. The developed method is demonstrated through a case study of a thermal management system (TMS) of an electric truck. It is shown that a small set of recurring system elements can be used to represent a large number of individual thermal interactions, within TMS components and, therefore, streamline modelling efficiency significantly.

Keywords: product development; model-based systems engineering (MBSE); system elements (solution elements); model reuse; battery electric vehicle (BEV); electric truck; thermal management system (TMS)

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1. Introduction

The complexity of today's products is increasing, partly due to the increasing presence of multidisciplinary interactions, e.g., the growing integration of mechanical, electrical, and thermal components in vehicles [1,2]. This is true for electric vehicles, in which systems such as the electromechanical drivetrain interact closely with the cooling system, collectively having a significant impact on vehicle efficiency.

At the same time, market demands are rapidly changing, thus pushing for accelerated development times [3]. In the political field, for instance, the politically motivated shift

from combustion-engine drivetrains to electromechanical drivetrains poses an immense challenge [4].

Virtual and model-based product development addresses this challenge by reducing development times by avoiding time-intensive physical prototypes [5]. In model-based product development, virtual system models are employed to verify technical requirements. These system models are intended to describe product behaviour and enable design decisions. Consequently, numerous calculation models have been developed to verify diverse product requirements. However, creating such system models including models is time-consuming due to the often multidisciplinary nature of system interactions and the large number of models required to adequately describe the product's behaviour. However, despite the availability of many models, the degree of model reuse remains low [6]. To enable fast, virtual product development, the reuse of models is essential for validating products based on existing models. This lack of reuse is often caused by the absence of standardized and reusable model libraries [6,7].

One approach to reducing the modelling effort is to structure system models into reusable model elements, referred to as **system elements** [8]. Based on these reusable system elements, system models can be aggregated and developed quickly and verified against requirements.

Modern software development approaches, such as model-based software engineering, already provide a solution for creating system models based on reusable elements [9,10]. However, transferring this approach to mechatronic products using model-based systems engineering (MBSE) is challenging as physical behaviour calculation models are needed to describe product behaviour for verification purposes [7,11].

MBSE system models, particularly their system elements, offer the potential to structure and reuse models as part of a model library. While a method for identifying system elements in mechanical systems already exists, **the identification of system elements in thermal systems remains an open challenge**. Transferring the approach from mechanical to thermal systems requires adapting the mechanical system elements, which focuses on the contact between two components [12]. In thermal systems, however, heat transfer does not necessarily occur between two components, which requires a more detailed investigation of the transferability. **Therefore, the goal of this paper is to develop a method for identifying system elements in heat-exchanging systems**.

The method for identifying reusable system elements in heat-exchanging systems presented in this paper is demonstrated using the use case of the thermal management system of an electric truck, as it is a complex system with numerous physical interactions.

The paper is structured as follows: Section 2 provides an overview of the state of the research in model-based systems engineering and system elements. Section 3 presents the research question and solution hypothesis. The method to identify system elements in heat-exchanging systems is presented in Section 4 while Section 5 demonstrates the method on the use case of the thermal management systems. Section 6 gives a discussion and Section 7 concludes the paper.

2. State of Research

Model-based systems engineering (MBSE) is an approach to the interdisciplinary development of mechatronic systems. When systems are decomposed, the result is a hierarchically structured system architecture. MBSE supports the system to be developed with a focus on its functions using a common, parameter-based system architecture.

MBSE encompasses three essential parts: methodology, tools (e.g., Cameo Systems Modeler), and modelling language (e.g., System Modeling Language SysML v1) [13]. At the core of MBSE is the system model, which serves as a central data base for integrating

and organising models across multiple disciplines. This system model should be built using **reusable system elements**, facilitating modularity and efficient development [14]. Collectively, these system elements form the complete system model. Each system element incorporates interfaces that define interactions within the system [15].

In MBSE, system elements are often described using SysML. This gives them an object-oriented character and enables their organization into reusable SysML libraries [16,17]. System elements exist, among other forms, in hardware. Hardware system elements represent components of physical system architectures, depict active structures, and include modules, assemblies, parts, etc. [2,18]. They describe functional and physical relationships and interact through material, energy, or signal flows [1,19].

For efficient reuse, system elements should be uniformly defined. Efforts have been made to map these system elements to the **lowest system hierarchy level** [20], where only elementary elements exist and further meaningful system decomposition is not possible. However, the literature discusses system elements at various system hierarchy levels [2,15], indicating that system elements can be either part of a system or a system in themselves [21,22]. In [2], for example, system elements are described at a higher-level system hierarchy such as a crank drive or a valve train. In [1], a camera represents a system element, whereas in [23], a bearing or radial shaft seal is classified as a system element. **In summary, there is currently no unified definition of the system hierarchy level for elementary system elements**.

The standards set by VDI 2206 [20] and VDI 2221 [24,25] provide an established process for developing mechatronic systems. Particularly important are the description of requirements, functions, and function-fulfilling principle solutions based on physical effects as well as verification through simulation models. The finite number of elementary functions defined by Koller [26] enables the functional decomposition of all overall technical functions. The decomposition allows systems to be divided into recurring functions, reducing complexity and streamlining the development.

MBSE methods for mechatronic systems streamline the process using digital models. Here, the goal is to increase the efficiency of product development through MBSE [1].

MBSE methods such as motego [7,12,26], CONSENS [27], FAS4M [23,28], MecPro^2 [29], SE-VPE [17], according to [30–32], support the modelling of mechatronic system architectures using system elements. These methods are fundamentally based on the established engineering methodologies of Pahl/Beitz [3], VDI 2221 [24], and VDI 2206 [20]. Within this framework, functional system architectures and principle solutions are modelled, in which the principle solutions represent system elements. These system elements realise specific functions based on physical effects.

The investigation into these MBSE methods reveals certain limitations. **They do not offer a seamless, parameter-based modelling approach for principle solutions that fulfil functions.** Specifically, there is no clear discussion on how models of physical effects can be integrated into functional system architectures to enable consistent, parameter-based modelling. This lack of integration is a significant challenge for the consistent representation of functional and physical relationships in system models of mechatronic systems.

Another critical gap is the lack of explicit consideration of the system hierarchy level at which system elements are represented. While the aforementioned methods avoid addressing this aspect, the contact and channel (C&C) approach is an exception [30]. In this approach, the force-transmitting surfaces of components are modelled as active surfaces and the force flow within a component is represented as connecting channel and support structures (CSS). Ref. [30] applies the C&C concept in SysML, providing system elements on a unified system hierarchy level. However, this approach does not address the integration

of diverse models, such as models of physical effects or complex calculation models, into the system model.

Ref. [32] takes a similar approach to [30] by incorporating the EHD (elastohydrodynamic) contact into an MBSE system model, demonstrating the potential of a unified level for system elements. Nonetheless, this approach primarily focuses on structuring the system model itself. It does not discuss the reusability of system elements in SysML libraries or propose a unified system hierarchy level for these elements.

Motego [12,26,33] introduces an MBSE-based method that utilizes **standardised**, **function-oriented system elements**, **called solution elements**, as the smallest reusable units. As shown in Figure 1, the solution element is the realisation of an elementary function, which is defined as a function that cannot be further decomposed and thus exists at **the lowest, elementary system hierarchy level** of a physical system architecture [34]. Elementary functions have input and output quantities, such as forces, which are represented as elementary flows, termed "EnergyFlow". For instance, in the elementary function *conduct force*, the input and output quantities are forces. The realisation of these elementary functions in a mechanical product is achieved by combining physical effects, active surfaces, and materials, forming what is referred to as the principle solution [3]. By extending the principle solution to incorporate domain-specific models, such as calculation models for specific purposes as well as workflows [35] that execute these calculations, the solution element is created.

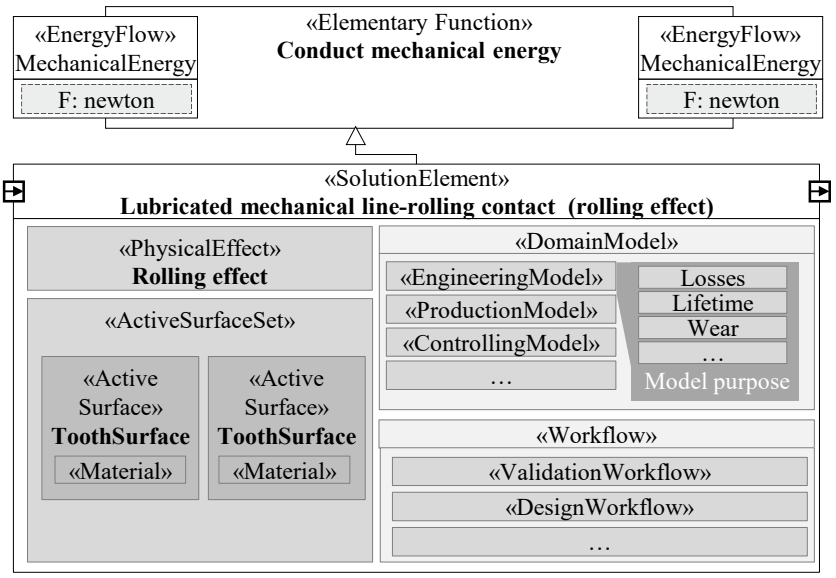


Figure 1. Overview of the solution element and the inner structure (arrow shows generalisation).

The identification of solution elements from existing electro-mechanical powertrains of electric vehicles can be achieved based on mechanical contacts [12]. By identifying and analysing mechanical contacts within a system, solution elements can be derived. This approach is applicable to mechanical systems that involve surface sets, such as the contact between a roller and a bearing ring (see Figure 1). However, solution elements of other domains such as heat-exchanging systems are not addressed. **A direct transfer from the mechanical to the thermal domain is not feasible.** In mechanical systems, contact occurs when two solid structures touch through a contact surface. In contrast, heat transfer can occur between solids and fluids without direct mechanical contact. An example of this is convection between a heated surface and a fluid, where a solid and a fluid interact without any direct contact between two solid structures.

In conclusion, an analysis of the state of research reveals that MBSE system elements are suitable for structuring models, enabling their reuse, and thereby accelerating product development. To facilitate effective reuse, system elements must be modelled on a consistent system hierarchy level and uniformly structured in model libraries. **However, the definition of a unified system hierarchy level has been hardly addressed in existing MBSE methods.** The motego method examines the system hierarchy level of mechanical systems and models so-called "solution elements" at the level of mechanical contacts. This establishes a consistent foundation for mechanical systems, such as the electro-mechanical drivetrain of an electric vehicle. Nevertheless, the application of this approach to heat-exchanging and heat-transferring systems, such as the thermal management system of electric vehicles, has not yet been explored.

3. Research Question and Hypothesis

Based on the lack of research on the transferability of the solution element identification approach to the thermal domain, as discussed in Section 2, this paper aims to explore how thermal solution elements can be identified in heat-exchanging systems. The research questions are as follows:

RQ1: *At which system hierarchy level can elementary thermal solution elements be identified in heat transfer systems?*

RQ2: *How can elementary thermal solution elements be derived at the identified system hierarchy level?*

The underlying hypotheses are:

H1: *The thermal interaction between media ("thermal contact") serves as the basis for identifying system elements and its system hierarchy level.*

H2: *By systematically classifying the physical processes involved in heat exchange, solution elements can be derived.*

4. Method to Identify System Elements in Heat-Exchanging Systems

4.1. Overview

The methodological steps chosen in this paper are based on both the problem-solving cycle of systems engineering (in German "Systemtechnik") [4] and the methods of classification systems [36]. These two approaches are combined to systematically address the research questions posed.

The problem-solving cycle of systems engineering is employed to determine the system hierarchy level of the elementary solution elements through system decomposition. This identified system hierarchy level, in the following called elementary system hierarchy level, serves as the foundation for further investigation. In this investigation, the methods of classification systems are applied to analyse and classify the thermal–physical processes involved in heat transfer. Subsequently, a classification procedure is developed, enabling the derivation of specific thermal solution elements. By combining these approaches, it is ensured that the investigation is conducted in a structured manner, enabling the identification of specific thermal solution elements.

In summary, the following three fundamental methodological steps are conducted:

I. Specifying requirements of thermal solution elements
II. Determining the system hierarchy level of the solution elements through system decomposition

III. Developing a classification procedure for thermal solution elements at the determined system hierarchy level

Once the requirements for the system element are specified in step I, the determination of the system hierarchy level follows in step II with the following three subordinate steps:

II. 1. Determine potential solution elements at different system hierarchy levels through the decomposition of existing systems (modules, components, contact, etc.).
II. 2. Analyse the potential solution elements at the respective system hierarchy level in terms of their functional and physical properties.
II. 3. Conduct an assessment by examining developed requirements and deciding on the system hierarchy level of thermal solution elements in MBSE.

In step III, further investigations are conducted at the system hierarchy level identified in step II, aiming at systematising and structuring the occurring heat-exchanging processes to define solution elements. Through an abstraction, similar heat-exchanging processes are to be grouped. The heat-exchanging processes refer to the physical effects and properties that act during heat transfer and contribute to the fulfilment of the function. By structuring the heat-exchanging processes and the related knowledge, the knowledge can be processed and transferred into a solution element. The result is a finite and recurring set of solution elements, developed based on similar and recurring heat-exchanging processes.

In order to facilitate the application of the developed method and classification, a procedural model is developed in the last step. This procedural model includes guiding questions to identify specific thermal solution elements and subsequently name them. In sum, the final steps are as follows:

III. 1. Classify heat-exchanging processes.
III. 2. Develop a classification procedure to identify specific thermal solution elements.

4.2. Specifying Requirements of Thermal Solution Elements

This section presents the identification of requirements (see Table 1) for solution elements of heat-exchanging systems. Therefore, the established development process, as outlined in VDI 2221, was examined in order to derive requirements for the solution element itself. This is intended to ensure that the solution elements can be applied within the development process.

Table 1. Developed requirements of solution elements.

Req. No.	Req. Title	Req. Description
R1	Specification	The solution element can be **linked to technical requirements**.
R2	Sub-function	The solution element cannot be divided into technically meaningful **sub-functions**.
R3	Subordinate reusable solution	The solution element does not contain any **subordinate reusable solutions**.
R4	Active surface	**Active surfaces** and pairs of active surfaces can be clearly assigned to the solution element.
R5	Physical effect	A **physical effect** can be assigned to the solution element that fulfils the function.
R6	Material	**Materials** can be assigned to the solution element.
R7	Active movement	An **active movement** can be clearly assigned to the solution element.
R8	Engineering models	Established **engineering models** are used at the same level as the solution element.
R9	Connection	The solution element can be **connected** with other solution elements to form a system architecture.
R10	Product neutral	The solution element is a **product-neutral** element and can, therefore, be **used universally**.

The modelling and mapping of requirements, functions, and solutions are of particular importance in order to achieve consistency and traceability of decisions. In consequence, it is defined that technical requirements should be allocated to the solution element (R1) to link requirements. As a system hierarchy level of the elementary solution elements is to be identified, the solution elements should not contain any subordinate functions (R2) or solutions (R3), but should themselves represent this level. This is intended to ensure that the correct elementary and not technically decomposable system hierarchy level is identified, thereby guaranteeing a high degree of reusability.

According to [24,34], the active surface, the physical effect, and the material are crucial for modelling a solution that fulfils an elementary function. Consequently, it is defined that the active surface (R4), the physical effect (R5), and the material (R6) can be assigned to the solution element. Furthermore, both the VDI 2221 and the other literature on design methodology, such as [37], describe the movement between active surfaces as a variable for analysis when searching for and modelling solutions. Therefore, the capability of assigning movement to the solution element is defined as requirement (R7). It should be noted that no relative movements between surfaces can also be assigned here, such as in cases where no relative movement occurs.

Engineering models are employed for the assessment of technical requirements. Consequently, established engineering models should be available at the same level (R8) as the system hierarchy level to be identified.

The connection of solution elements is a crucial step in the development of system architectures, as it allows for the aggregation of architectures. To examine this aspect and incorporate it into the solution element, the requirement "connecting solution elements" (R9) is defined.

Lastly, the necessity for product neutrality, i.e., convective heat transfer at the wall, of the solution element is established (R10) in order to achieve the highest possible degree of reuse. If the solution element is already product-specific, such as a battery cooling channel, its reuse in similar solutions is reduced. Therefore, it should be as product-neutral as possible to allow for its application in different implementations.

4.3. Determining the System Hierarchy Level of the Solution Elements Through System Decomposition

The aim of this section is to identify a system hierarchy level of thermal solution elements for heat-exchanging systems.

The investigation into the system hierarchy level to be identified is conducted through the decomposition of a representative system. In this step, possible system hierarchy levels are determined, analysed, and evaluated. To illustrate the identified system hierarchy levels, different scales are used, inspired by tribology. These range from macroscopic to microscopic scales.

Subsequently, these identified system hierarchy levels are analysed and evaluated across scales from the macroscopic to the microscopic level. Based on this evaluation, a decision is finally made regarding the system hierarchy level of the elementary solution elements. The approach is demonstrated using a plate heat exchanger as an example.

4.3.1. Determine Potential Solution Elements at Different System Hierarchy Levels

The first step involves determining the system hierarchy level of potential solution elements in order to facilitate analysis and comparison in the subsequent step. Through this investigation, an appropriate degree of abstraction is determined, which enables a function-oriented structuring of models. To illustrate the general investigation of the system hierarchy level, the example of the plate heat exchanger is used to highlight the traceability of the analysis (see Figure 2).

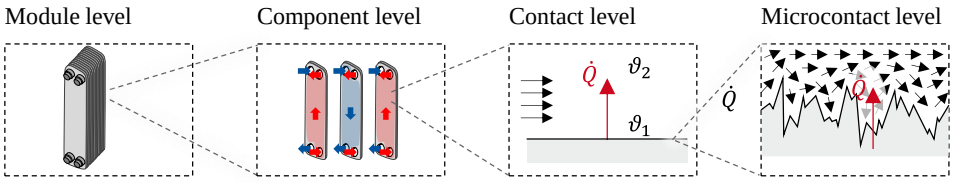


Figure 2. Investigation into different system hierarchy levels by decomposition of solution elements on the example of the heat exchanger (module level based on [38]; component level based on [39], arrows show hot (red) and cold fluid flow; contact level and microcontact level, black arrows show fluid flow and red arrows show heat flow).

The approach of product modularisation [3] is particularly relevant here, as it also examines the formation of reusable units. Specifically, the decomposition of a system into functional and physical elements is of importance. The modularisation of a system results in different system hierarchy levels, which are illustrated in Figure 2. These levels are referred to here as module level, component level, contact level, and microcontact level.

The initial level of analysis is that of the total heat exchanger. This is a purchased component that is a common reusable element in heat-exchanging systems. The system comprises all the plates, seals, screw connections, etc.

The next step is to consider the heat-exchanging plate level. This is the unit of the heat exchanger, responsible for facilitating the transfer of heat. The number of plates or their geometric dimensions are determined at this level. These plates are arranged in parallel with a directed volume flow, facilitating the transfer of heat.

At the system level below, macroscopic fluid-wall heat transfer is considered. In heat-exchanging processes, individual geometries are considered and modelled at a heat-transferring wall. The wall is assumed to be a macroscopic surface without roughness. Furthermore, contact is assumed to occur between the surfaces and the fluid, whereby the fluid flows past the surface.

The final system hierarchy level that is considered here is that of microscopic fluid-wall heat transfer. At this level, the investigation is focused on microscopic effects that are influenced by roughness, as is the case with boiling micro-turbulence. All identified system hierarchy levels are illustrated in Figure 2.

4.3.2. Analysis of the Potential Solution Elements at the Respective System Hierarchy Level

This section analyses the system hierarchy level identified in Section 4.3.1. At each hierarchy level, solution elements are defined based on the basic structure of the solution element (see Figure 1). This ensures that the identified solution elements can be utilised in MBSE to model system architectures effectively. These elements of the basic structure—elementary function, elementary flow, active surfaces, and physical effect—are collectively referred to as "basic characteristics" in the following sections. Furthermore, the basic characteristics enable a structured differentiation and comparison of solution elements based on their properties. The identified solution elements at each system hierarchy level are briefly introduced to illustrate their structure and function.

While total heat exchangers and heat transfer plates are functionally reusable units, the total heat exchanger cannot be directly associated with a specific active surface or the function-fulfilling physical effect. In the case of heat transfer plates, it is possible to generally assign the physical effect, but there are numerous active surfaces, making a clear allocation of the active surfaces challenging. In contrast, the macroscopic fluid-wall heat transfer allows both the active surface and the corresponding physical effect to be assigned to the active surface. It is also possible to assign the elementary function and the functional flow.

At the system hierarchy level of the solution element microscopic fluid-wall heat transfer, the elementary function and functional flow are the same as at the macroscopic fluid-wall heat transfer. The difference lies in the active surface and the physical effect. The active surface here is not idealised but has a certain roughness, and the physical effect acts at the peaks of the roughness.

Table 2 shows a comparison of the identified solution elements and their characteristics.

Table 2. Thermal solution elements from procedure step "Determine potential solution elements" and their analysis based on the characteristics.

System Hierarchy Level	Solution Element	Elementary Function	Functional Flow	Active Surfaces	Physical Effect
Module level	Total heat exchanger	Separate or collect energy	In: Volume flow; Out: Volume flow	Not clearly determinable	Not clearly determinable
Component level	Heat transfer plates	Separate or collect energy	In: Volume flow; Out: Volume flow	Occurring heat-emitting plates	Convection at the plates
Contact level	Macroscopic fluid-wall heat transfer	Separate or collect energy	In: Volume flow, heat flow; Out: Volume flow	Single heat transferring surface with the wetted fluid	Convection on idealised surface
Microcontact level	Microscopic fluid-wall heat transfer	Separate or collect energy	In: Volume flow, heat flow; Out: Volume flow	Surface roughness and wetted fluid	Convection on roughness

4.3.3. Assessment and Decision on the System Hierarchy Level of the Solution Elements

In this section, the identified solution elements from Section 4.3.2 are evaluated in terms of the fulfilment of the requirements outlined in Section 4.2 and Table 1. This allows the appropriate system hierarchy level for thermal solution elements to be determined. Each possible solution element identified from the system hierarchy level is individually evaluated against the defined requirements.

The degree of fulfilment of each requirement is assessed using a three-category evaluation system. The following categories are applied: (3) applies, (2) neutral, and (1) does not apply. Additionally, arguments for the assessment are provided.

The assessment results are summarised in Table 3. In the table, the requirement number defined in Table 1 is listed on the left. The middle column contains the assessment score, while an explanation of the score is provided in the right column. At the bottom, the sum of the assessment scores for the corresponding system hierarchy level is presented to facilitate a better comparison of the individual system hierarchy levels. Table 3 shows the assessment table for the system hierarchy level of the solution element "macroscopic fluid-wall heat transfer".

The solution element and its system hierarchy level "Macroscopic fluid-wall heat transfer" realises elementary functions (R2) while allowing overall systems aggregation (R9). It is a sufficiently elementary level to enable the assignment of active surfaces (R4), physical effects (R5), materials (R6), and active movement (R7). Furthermore, engineering models are also modelled at this level (R8). Due to the sufficient product neutrality (R10), the solution element can be reused to aggregate overall systems (R9).

In the same manner, the system hierarchy levels and corresponding solution elements identified in Section 4.3.1—"Total heat exchanger," "Heat transfer plates," and "microscopic fluid-wall heat transfer"—were evaluated against the requirements in a table. The relevant tables can be found in Appendices A–C. The following provides a brief summary of the key results from the evaluation of each system hierarchy level.

Table 3. Assessment of the macroscopic fluid-wall heat transfer solution element with regard to the requirements of Table 1.

Req. No	Assessment	Argument
R1	3	Linking with basic requirements is possible.
R2	3	Basic element of heat transfer, there are no subordinate functions here from a functional orientation perspective.
R3	3	Subordinate reusable solutions cannot be found from a product development perspective.
R4	3	Active surfaces can be assigned by the macroscopic surface.
R5	3	Assignment of physical effects is possible; therefore, this element is used for description in physics.
R6	3	Assignment is possible because the basic system of surface and fluid is considered.
R7	3	Assignment is possible because the basic system of surface and fluid is considered, so moving/no moving surface or fluid.
R8	3	Heat transfer coefficients and turbulence are calculated at this level.
R9	3	Aggregation is possible, as both fluid and wall surfaces are considered.
R10	3	In the field of heat transfer, it is product-neutral, as different systems can be aggregated with this element.
Assessment sum	**30**	

Total heat exchanger: The total heat exchanger is an inadequate solution due to the inclusion of numerous subordinate functions (R2) and solutions (R3).

Heat transfer plates: The concept of heat transfer plates is useful in principle, but further subordinate elements can be identified (R2 and R3). In addition, individual active surfaces are missing (R4), which are considered together here.

Microscopic fluid-wall heat transfer: This level is unsuitable for product development, particularly in terms of aggregating the elements into an overall system (R9). Energy flows, for example, must be modelled at this level in such detail that individual force flows between roughness peaks and fluid must be represented. Furthermore, mapping roughness in the initial stages of product development is also a challenging task, as it is not focused in this stage of the development process.

In conclusion, the investigation has demonstrated that the macroscopic fluid-wall heat transfer level is a meaningful system hierarchy level for solution elements. Table 4 presents a comparison of the total assessment scores for each system hierarchy level and its solution elements.

Table 4. Comparison of the assessment and decision of the system level of thermal solution elements.

Solution Element	Total Heat Exchanger	Heat Transfer Plates	Macroscopic Fluid-Wall Heat Transfer	Microscopic Fluid-Wall Heat Transfer
Assessment sum	11	18	**30**	25
Decision			**Selected system hierarchy level**	

4.4. Developing a Classification Procedure

In this section, a classification procedural is developed to enable the identification of reusable thermal solution elements. To develop a limited number of such solution elements, a wide range of existing technical systems must be abstracted. Classification is intended to

be utilized here to classify and group physically similar and thus abstracted systems. This allows for the development of a finite number of solution elements that can be used for the structuring of models and the creation of reusable model libraries.

4.4.1. Classifying Heat Exchanging Processes

In order to derive a finite number of solution elements, heat transfer systems are analysed and structured based on their physical and functional processes within this section.

A classification with specific characteristics is used for structuring. To determine these characteristics, the literature on design methodology [34,37] as well as the literature on heat transfer and fluid mechanics [40–42] was reviewed. As a result, only a reduced number of distinct elementary functions can be assigned to the identified system hierarchy level of heat transfer systems (see Table 5). The identified functional flows are: heat flow and mass flow. The most frequently occurring elementary functions are: conduct, separate, convert, and apply.

Table 5. Classification characteristics for thermal solution elements.

	Classification Characteristics					
	Elementary Function	**Elemental Function Flow**	**Medium, Mixture**	**Phase Transition**	**Active Surface**	**Physical Effect**
Specification	Conduct	Heat flow	Solid	Evaporating	Planar	Forced convection
	Separate	Mass flow	Liquid	Condensing	Curved	Natural convection
	Convert		Gas	Melting	Cylinder	Conduction
	Apply		Suspension	Freezing		Radiation
			Aerosol	Sublimating		
			Emulsion	Resublimating		

The realisation of these elementary functions through physical effects can be reduced to a few key physical effects: forced convection, natural convection, conduction, and radiation. For the purposes of this research, the identified active surfaces were grouped into the following categories: planar, curved, and cylindrical.

According to the literature on heat transfer and fluid mechanics (e.g., [40–42]), further characteristics used to describe thermal interactions are: the interacting media (liquid-solid, etc.); substances/mixtures (homogeneous/heterogeneous); phases of the substances (one phase, two phases); fluid type (compressible/incompressible); phase transitions (vaporizing, condensing, etc.); states of aggregation (liquid, gaseous, solid); and flow state (flowing, resting).

The mixtures are carried along as homogeneous and heterogeneous mixtures, e.g., to be able to include liquids or gases as homogeneous mixtures (e.g., refrigerant) without having to separate them into chemical elements. The heterogeneous mixtures are included to be able to describe e.g., heat-conducting pastes as a suspension without needing to consider the chemical components.

The results of the analysis and the classification characteristics developed are summarised in Table 5. The table lists all mentioned characteristics in a compressed form to provide a clear overview. To avoid redundancies, for example, it is not specified that a solid medium is also an incompressible fluid. For the purpose of this study, mentioning a fluid is sufficiently precise.

4.4.2. Development of Classification Procedure to Identify Specific Thermal Solution Elements

Based on the classification characteristics of a thermal interaction listed in Table 5, a decision tree (see Figure 3) is proposed that aims at guiding a user when identifying solution elements (see Roman numerals in Figure 3). The starting point is a single identified heat transport between surfaces and/or fluids. Following the activities within the classification procedure, we propose to define the name of the thermal solution element as: [Emitting medium-receiving medium] heat transfer with [phase transition] over [active surface] ([physical effect]).

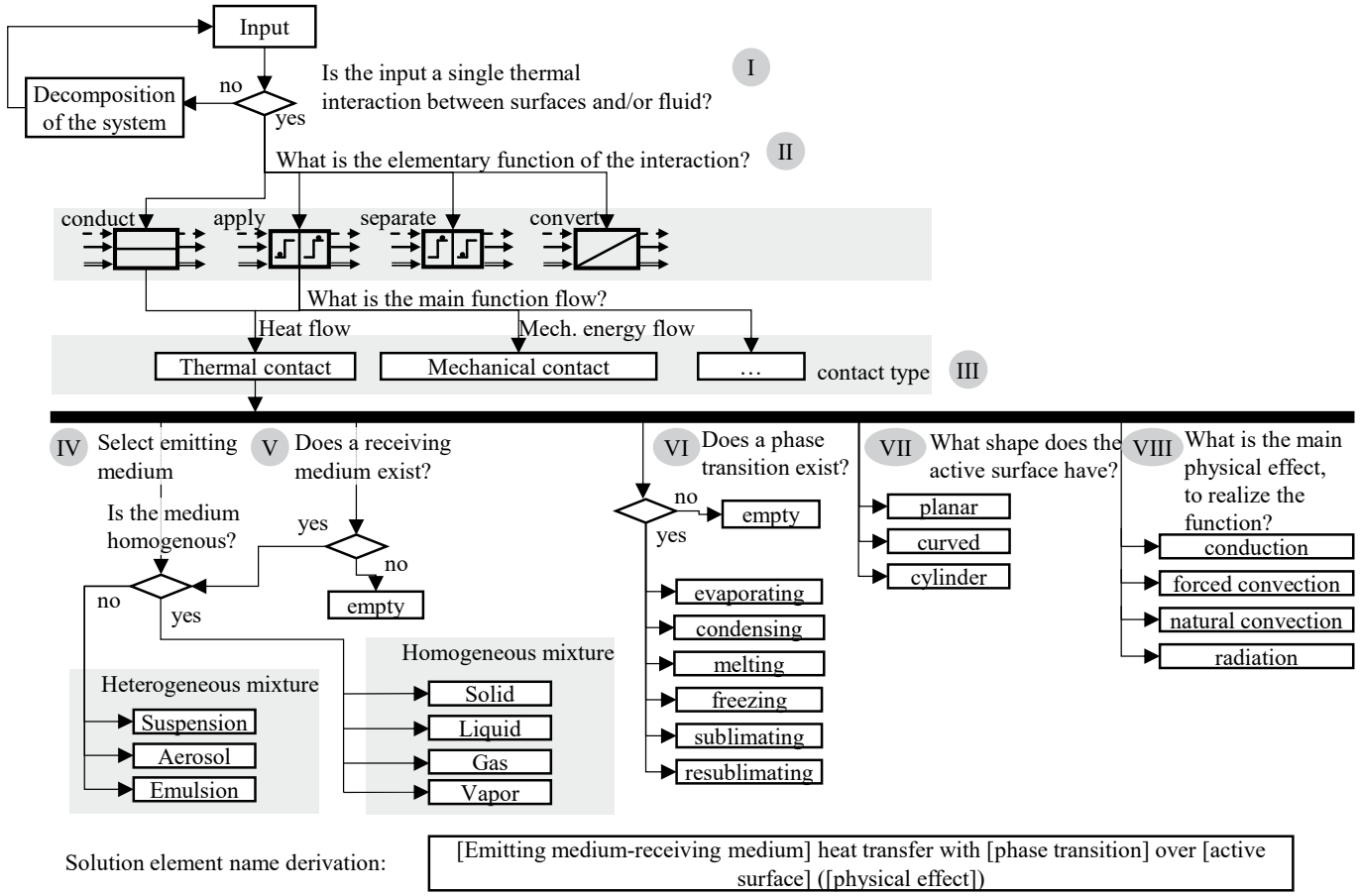


Figure 3. Classification procedure in a decision tree for deriving thermal solution elements.

An example application of the classification procedure developed in Figure 3 is illustrated in Figure 4. For clarity, the input-process-output representation is used. It clearly illustrates the specific inputs, how they are processed, and what the resulting output of a process is. For a simple demonstration, the oil-coolant heat exchanger plate was chosen. The Roman numerals in Figure 4 (centre) represent the intermediate steps and indicate the corresponding intermediate results. On the output side of Figure 4 (right), all of these interim results are consolidated under the name of the solution element.

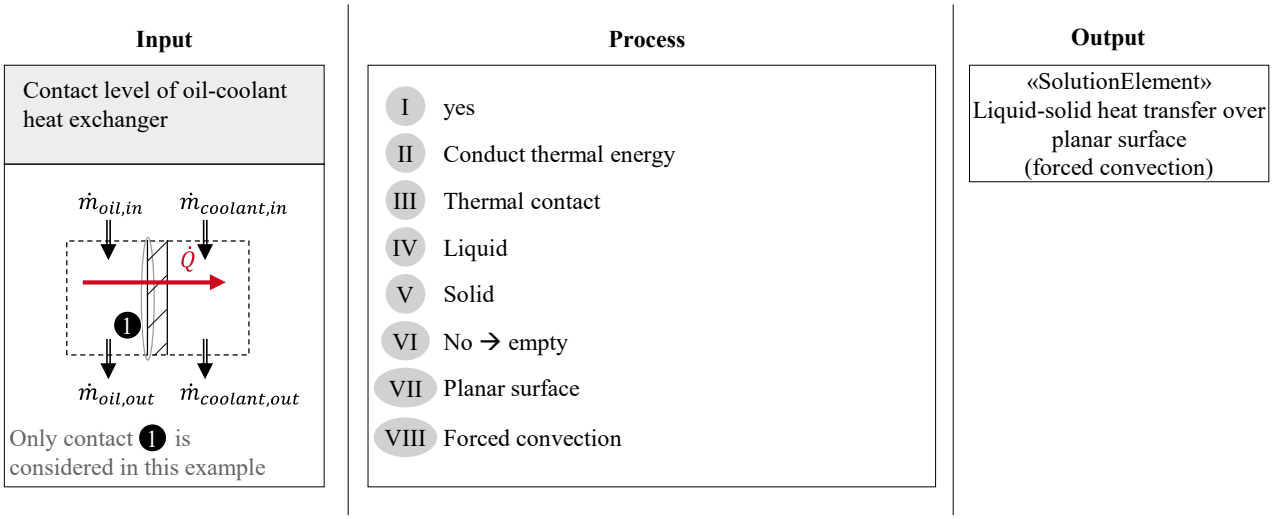


Figure 4. Example of applying the classification procedure on one thermal contact within the oil-coolant heat exchanger.

4.5. Interim Conclusion

System hierarchy level

The investigation was demonstrated using the example of a plate heat exchanger, as this system is widely used in heat transfer systems and, due to its system complexity, serves as a good illustration for the decomposition conducted.

The system hierarchy level of the solution element "Macroscopic fluid-wall heat transfer" is an appropriate level at which to model solution elements, offering a unified, reusable, and function-oriented approach. This is due to the effective leverage between the mapping of elementary functions and physics, which allows for the aggregation of total systems.

At a lower system hierarchy level than "**Macroscopic fluid-wall heat transfer**", a separation of the physical processes becomes so granular that it becomes challenging for product developers to aggregate total systems from it again. It is, therefore, proposed to integrate high-fidelity models from the system hierarchy level of "**Microscopic** fluid-wall heat transfer" into the higher level of "**Macroscopic** fluid-wall heat transfer" as engineering models. This allows such detailed models to be utilised and re-used in product development as required to assess specific requirements.

At a system hierarchy level one above the "Macroscopic fluid-wall heat transfer", the assignment of active surfaces is not clear. In order to facilitate the clear assignment of active surfaces, a system level is required at which individual active surfaces can be assigned.

Classification procedure

The fundamental physical and functional processes were classified in order to facilitate sufficient differentiation and to organise and structure the knowledge of physical processes. This enables the knowledge to be reused effectively. In order to facilitate clear classification, a set of characteristics was developed with the objective of enabling sufficient differentiation of the processes in question, thereby ensuring their transferability to the solution element. As mentioned, the fundamental characteristics of the classification were derived from the established design methodology approaches. By analysing the heat-exchanging processes, further discipline-specific features were incorporated that provide an adequate description of the thermal interaction.

The classification of the thermal contact is possible with only six characteristics, which allows for the definition of solution elements. The classification procedure is displayed in a

decision tree and its accompanying questions facilitate the identification of standardised thermal solution elements on the basis of thermal interactions.

5. Case Study

The demonstration of the classification procedure for identifying solution elements is presented in this section.

The example system, a thermal management system of an electric truck, is briefly introduced, followed by a detailed analysis of thermal interaction at the contact level. The contact level is the level where individual active surfaces transfer heat and is selected for the identification of solution elements as outlined in Section 4.3 and will be used in this section. The identified subsystems at this level are subsequently processed through the decision tree, enabling the derivation of specific solution elements.

5.1. System of Investigation: Thermal Management System of a Battery Electric Truck

This section provides a brief overview of the thermal management system (TMS) of the electric truck. It consists of four interacting circuits: one refrigerant circuit, two coolant circuits, and one oil-coolant circuit (see Figure 5) [43,44]. Those circuits fulfil the overall function of managing heat, which means cooling on the one hand and heating on the other.

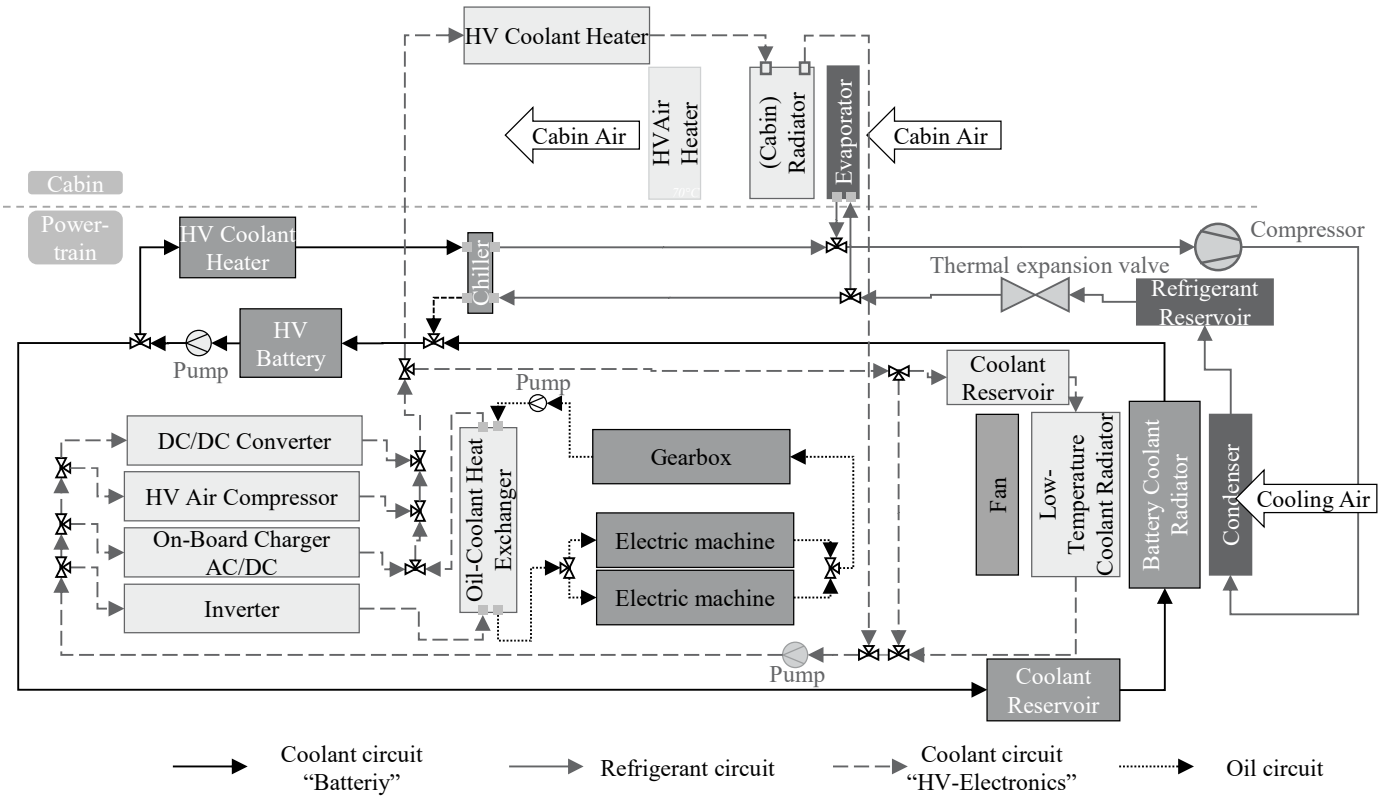


Figure 5. Schematic representation of an electric truck thermal management system based on [43,44].

The purpose of the refrigerant circuit is to maintain the cabin temperature. It contains a condenser, expansion valve, evaporator, refrigerant reservoir, and compressor. The compressor compresses the gaseous refrigerant from the evaporator. The refrigerant, at a high temperature and pressure, is directed to the condenser. In the condenser, air from the environment is used to remove the heat from the refrigerant, which causes it to liquefy. In the next component, the expansion valve, the pressure of the liquid refrigerant is reduced by a nozzle, which is accompanied by an increase in volume and a decrease in temperature.

A 2-phase mixture is present, which absorbs the heat from the cabin in the evaporator and thus becomes gaseous again [45].

The refrigerant circuit is linked to the battery cooling circuit through a chiller, enabling additional cooling of the coolant circuit when the battery requires enhanced cooling. The coolant circuit further consists of the battery coolant plate (part of the HV battery in Figure 5), which transfers heat from the battery cells to the coolant. A pump delivers the coolant through a coolant reservoir to the battery coolant radiator. There, the heat is transferred to the cooling air, resulting in a reduction of the coolant temperature. The medium then flows to the battery to absorb heat again. A valve connects the battery coolant circuit to the refrigerant circuit via an HV coolant heater and the chiller. This heater is used when the battery needs to be warmed at low outside temperatures [43].

Another cooling circuit is the low-temperature circuit (see Figure 5). Its main function is to cool the battery charger, inverter, and other HV electric components such as the HV air compressor (e.g., for the braking system). The heat from those components is transferred to the coolant via different heat exchangers and fed to the low-temperature coolant radiator via a coolant reservoir. In the cooler, the heat is transferred to the air. A pump provides a volume flow that moves the fluid from the low-temperature coolant radiator to the components that need temperature conditioning (e.g., two inverters for each e-motor, charger, and air compressor) [43].

In order to increase the coolant temperature of the low-temperature circuit in a cold environment and thus improve the warm-up behaviour of the components at cold start, an HV coolant heater is used (see Figure 5). The HV coolant heater is connected upstream of the cabin radiator and electrically heats the coolant. Another sub-function of the low-temperature coolant circuit is to transfer the waste heat from the high-voltage electric components to the cabin through the cabin radiator. If the waste heat is not sufficient and thus the cabin temperature is still too low for the driver, an HV air heater can be used to raise the cabin temperature (see Figure 5). In this case, after the cabin radiator, the coolant does not flow through the low-temperature coolant radiator but is supplied to the components to be cooled via a valve.

The last circuit is the oil circuit. It is connected to the low-temperature coolant circuit via an oil-coolant heat exchanger. There, heat is transferred from the electric machine (s) and the gearbox. An oil pump draws oil from the oil sump in the gearbox and delivers it through the heat exchanger to the electric machines. The oil absorbs the waste heat from the electric machines and is then fed to the gearbox again, where it tempers and lubricates both the gear meshes and the bearings. With this solution, the temperature control and the lubrication are provided by a single medium [44].

The introduction of the TMS with its circuits demonstrates many physically interacting systems are required to fulfil an overall function. Additionally, within these systems, there is a multitude of various thermal interactions. A reduction of this complexity can be achieved through the structuring and classification of the systems as presented in Section 4.4.2.

5.2. Application of the Approach on Heat Exchanging Systems

To illustrate the application of the approach, the refrigerant circuit is presented in detail in this section, while the validation of the other circuits can be found in Appendix D. Each heat-exchanging component is described on the contact level and analysed in terms of thermal processes. Subsequently, the classification according to Section 4.4.2. is performed to derive the solution elements.

The individual components of the refrigerant circuit are depicted in Figure 6, with two representations provided for each component. On the left, the component is shown schemat-

ically, while on the right, a detailed view of the contact level is presented. In this detailed view, individual thermal interactions are numbered using black circles with numbers.

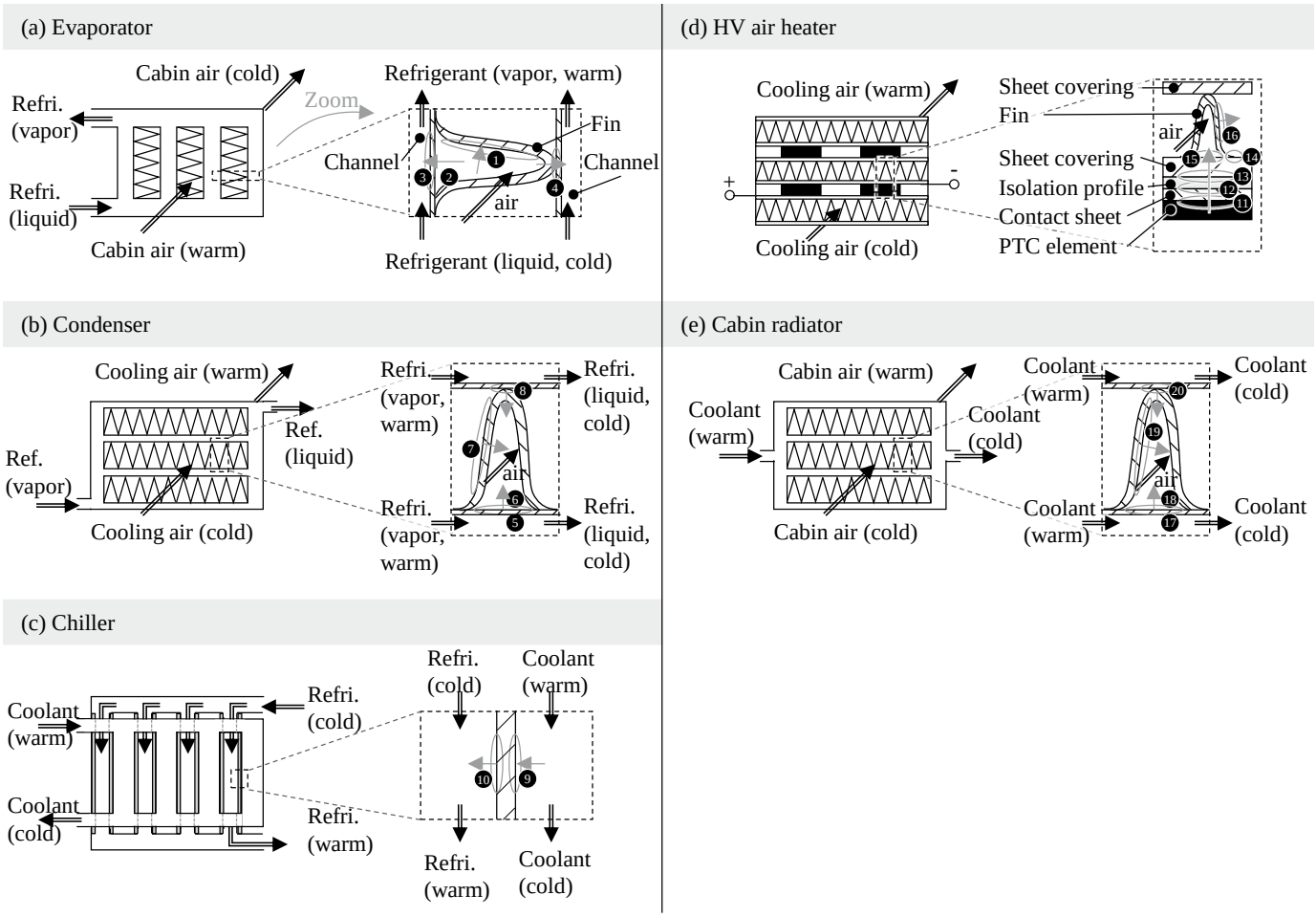


Figure 6. Heat transferring components in the refrigerant circuit, (**a**) evaporator [46], (**b**) condenser [47], (**c**) chiller [48,49], (**d**) HV air heater [50,51], (**e**) cabin radiator [52,53]. For each component, the illustration on the left visualises the entire component, while the image on the right shows a section at the level of thermal interaction. Those single thermal interactions are indicated by black circled numbers. Those interactions will be processed to derive thermal solution elements.

Within the refrigerant circuit, the structure of the evaporator is shown in Figure 6a. The refrigerant flows into the system where heat is transferred from the cabin air to the refrigerant. A detailed zoom shows the individual thermal interactions between the elements and provides an analysis at the level of the active surfaces (see Figure 6). The refrigerant channels and a fin in between can be seen. Heat is transferred convectively from the air to the fin (curved surface), directly to the channel (planar surface), or by conduction from the fin to the channel (surface contact). In the channel, heat is also transferred to the refrigerant by conduction. In total, due to the heat transfer, the refrigerant evaporates [46].

In the condenser, heat is transferred from the refrigerant to the cooling air (Figure 6b). Channels of gaseous and then liquefied refrigerant with a fin in between are located at the active surface level. Conduction transfers part of the heat flow from the channel to the fin after the heat has been transferred convectively from the refrigerant to the channel surface. Cooling air flows through the fin, absorbing heat from the refrigerant convectively: either from the surface of the channel to the air or from the fin to the air [47].

The chiller enables a heat exchange between the two respective volume flows (Figure 6c). At the contact level, heat is transferred by convection from the coolant to the wall, where it is conducted and then transferred convectively to the refrigerant [48,49].

In order to increase the temperature a HV air heater (Figure 6d)) is used. A positive temperature coefficient thermistor (PTC) element generates heat using electricity. This heat is mainly transferred to the contact plate (aluminium) by thermal conduction. The contact plate is connected to the fins through which the air flows. The heat is transferred either convectively from the contact plate to the air or via the fins to the air. More details are illustrated in Figure 6 [50,51].

The working principle of the (cabin) radiator is shown in Figure 6e). The coolant flows into the radiator and transfers heat to the cabin air. The detailed sketch is very similar to that of the condenser, except that the coolant is cooled by the cabin air without changing the state of aggregation. The heat from the coolant is transferred convectively to the channel wall and then to the air. At the same time, the heat is conducted to the fin and then transferred to the air by convection [52,53].

5.3. Identifying Thermal Solution Elements in Heat Exchanging Systems

In the final step, the thermal interactions from Section 5.2. are processed using the classification procedure outlined in 4.4.2. The results of this application are presented in Table 6.

Table 6. Derived thermal solution elements with corresponding heat-exchanging systems.

Number of Interactions in Figures 6 and A1–A3														Derived Thermal Solution Element by Applying the Classification Procedure of Figure 3
1														Gas-solid heat transfer over curved surface (forced convection)
									34					Gas-solid heat transfer over cylinder surface (forced convection)
2														Gas-solid heat transfer over planar surface (forced convection)
		9		17						36				Liquid-solid heat transfer over planar surface (forced convection)
	7		16	19										Solid-gas heat transfer over curved surface (forced convection)
	6		15	18										Solid-gas heat transfer over planar surface (forced convection)
						27		35				51		Solid-liquid heat transfer over cylinder surface (forced convection)
					24		33		37	46	50			Solid-liquid heat transfer over planar surface (forced convection)
													52	Solid-liquid heat transfer over curved surface (forced convection)
4	8		11–14	20	21–23	25–16	28–32			38–43	47			Solid-solid heat transfer over planar surface (conduction)
										44	48			Solid-suspension heat transfer over planar surface (conduction)
3		10												Solid-vapour heat transfer with evaporating fluid over the planar surface (forced convection)
										45	49			Suspension-solid heat transfer over planar surface (conduction)
	5													Vapour-solid heat transfer with condensing fluid over the planar surface (forced convection)
Evaporator	Condenser	Chiller	HV air heater	Cabin radiator *	HV coolant heater	HV battery	DC/DC Converter	HV compressor	Oil-coolant heat exchanger	Inverter	On-board charger	Electric motor	Gearbox	* is equal to the low-temperature radiator and battery coolant radiator
Systems/components of circuits														

Table 6 lists all identified and derived thermal solution elements of the entire TMS. These were derived from the thermal interactions shown in Figure 6 and Appendix D Figures A1–A3. Each thermal interaction is numbered by black circled numbers to illustrate the mapping to the solution element in Table 6. In total, over 300,000 thermal interactions can be reduced to only 14 thermal solution elements.

6. Discussion

The application of the developed classification procedure in the case study has confirmed the method's applicability. The selected thermal management system (TMS) is sufficiently complex, featuring numerous thermal interactions between circuits and components (see Section 5.1).

The proposed method (see Section 4.4.2) reduces all thermal interactions within the complex TMS by applying essential classification characteristics. These characteristics were systematically derived (see Section 4.4.1) with a focus on functional and physical relationships, which are particularly necessary for developing MBSE system models of heat-transferring systems.

The method enables the identification of only 14 thermal solution elements from over 300,000 thermal interactions (see Section 5.3). This suggests that the entire system can be modelled in MBSE using just these few solution elements, demonstrating their reusability and reducing the complexity of MBSE modelling.

If, in the next step, these solution elements are enriched with various calculation models (as seen with the mechanical solution elements in [54]), the initial modelling effort can be significantly reduced through reuse

Since the method is based on fundamental principles of heat transfer, it can be applied to other heat-exchanging systems, such as an additional subsystem within the presented TMS (see [55]) or the cooling system of a wind turbine (e.g., see [56]). For example, the heat exchanger in the wind turbine system described in [57] has a similar structure to the oil-coolant heat exchanger shown in Figure A2. In particular, at the contact level, there are sufficient similarities to suggest that the method can also be effectively applied in these cases.

The application of the method to the case study has revealed certain limitations. In particular, at the contact level, additional physical interactions beyond thermal effects were observed. Specifically, fluid-mechanical interactions were identified within the TMS, such as those in the pump and valve. Since these interactions belong to the domain of fluid mechanics rather than heat transfer, further research is needed to address them.

7. Conclusions

Current MBSE methods do not yet provide a uniform system level for modelling heat-transferring systems within MBSE system models. In this paper, the system level and the corresponding elementary system elements (solution elements) were examined (see Section 4.3). Subsequently, a classification was developed to derive standardised MBSE system elements at this identified system level (see Section 4.4.2). The results of the investigation can be summarised as follows:

- As a result of the systematic investigation of system levels, the standardized system level for elementary thermal system elements is the macro contact level, such as the physical interaction between a fluid and a wall surface.
- The developed method offers a guided approach to derive standardised system elements on a uniform system level from existing thermal systems using defined guiding questions (see Figure 3).
- Based on the case study of the thermal management system (TMS), it was demonstrated that over 300,000 individual thermal interactions can be reduced to just 14 recurring system elements.
- These system elements capture both functional and physical relationships and can be utilised to model MBSE system architectures.

Further research is needed to investigate additional elementary system elements that are essential for modelling fluid-mechanical systems, such as pumps and compressors, within the MBSE framework.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MBSE	Model-based systems engineering
TMS	Thermal management system
BEV	Battery electric vehicle
VDI	Verein Deutscher Ingenieure
SysML	System Modeling Language
CSS	Contact and support structure
EHD	Elastohydrodynamic
R	Requirement
HV	High voltage
LV	Low voltage
AC	Alternating current
DC	Direct current
PTC	Positive temperature coefficient
IGBT	Insulated-gate bipolar transistors
F	Force
$\dot{Q}$	Thermal energy flow
ϑ	Temperature
$\dot{m}$	Mass flow

Appendix A

Table A1. Assessment of the Total Heat Exchanger with Regard to the Requirements Made.

Req. No	Assessment	Argument
R1	1	Due to the lack of detailing, subordinate requirements such as the dimensions of the panels can be assigned.
R2	1	Further technical sub-functions can be identified: Sealing, insulating, conducting, etc.
R3	1	Subordinate and reusable solutions can be identified: Gaskets, plates, bolting, etc.
R4	1	Not possible, as there are too many different active surfaces with different functions.
R5	1	Many active effects, allocation of individual effects is not possible.
R6	1	It is not possible to allocate individual materials at this level.
R7	1	It is not possible to allocate individual active movements at this level.
R8	1	Losses, heat flows, turbulence, etc. are calculated at a subordinate level.
R9	2	Connecting is fundamentally possible, but only at higher levels such as the cooling circuit.
R10	1	Not a neutral element, as it is a specific assembly.
Assessment sum	**11**	

Appendix B

Table A2. Assessment of the Heat Transfer Plates with Regard to the Requirements Made.

Req. No	Assessment	Argument
R1	2	Linking is possible, but detailed requirements are not.
R2	1	Further technical sub-functions can be identified: Sealing, insulating, and conducting.
R3	2	Subordinate and reusable solutions can be identified, such as the individual panels.
R4	2	Active surfaces on the panels are possible, but the panels consist of subordinate active surfaces (heat-exchanging surfaces, sealing surfaces, etc.).
R5	2	Possible in principle, but it is not possible to clearly assign the physical effect at this level.
R6	2	The assignment of individual materials is not directly possible at this level.
R7	2	Further technical sub-functions can be identified: Sealing, insulating, and conducting.
R8	2	Temperature curves, heat flows, and heat transfer coefficients are calculated on individual panels or surfaces.
R9	2	Basic connecting is possible, but the plates appear as a packet.
R10	1	Subordinate and reusable solutions can be identified, such as the individual panels.
Assessment sum	**18**	

Appendix C

Table A3. Assessment of the Microscopic Fluid-Wall Heat Transfer with Regard to the Requirements Made.

Req. No	Assessment	Argument
R1	2	Requirements for the microscopic surface are more likely than for the microscopic surface, even if they exist.
R2	3	Very detailed basic element of heat transfer, but from a functional point of view it is the same function as at the macro level.
R3	3	Subordinate reusable solutions cannot be found from a product development perspective.
R4	2	Very detailed active surfaces, challenging when aggregating to the wall surface.
R5	3	Assignment of physical effects is possible in principle, up to microscopic effects.
R6	3	Allocation is possible as the basic system of surface and fluid is considered.
R7	3	Allocation is possible as the basic system of surface and fluid is considered.
R8	2	Calculations are carried out but with a very detailed question of a fundamental research nature.
R9	2	Aggregation becomes challenging at this level due to the very detailed scale.
R10	2	Very detailed basic element of heat transfer, but from a functional point of view it is the same function as at the macro level.
Assessment sum	**25**	

Appendix D. Detailed Analysis of Heat Exchanging Systems Within the Coolant Circuits and Oil Circuit

The battery coolant circuit is displayed in Figure A1. The HV coolant heater is fed with electrical energy and can be used to increase the temperature of the low-temperature circuit. Coolant flows into the system, convectively absorbs the electrically generated heat

while flowing through the meandering profile, and flows out of the system. In this example, the heat is generated by a PTC element and conducted to the heater rib via various layers (electrodes, electrical insulation). Since the system is mechanically clamped, there is a pressed surface contact between the layers, and the heat is transferred accordingly by thermal conduction. At the rib, heat is then transferred convectively from the fin surface to the coolant [58].

The HV battery is cooled by a cooling plate in which a copper tube is inserted (see Figure A1). The battery packs are located over the cooling pad and transfer heat during operation or require heat for cold starting in winter. This bi-directional heat flow is described only once by the heat exchange from the battery to the cooling channel. The battery heat is transferred by thermal conduction to the cooling pad (silicone) and the copper tube, to then be convectively transferred to the coolant in the tube via a cylinder surface. The battery heat is then transmitted to the ambient air via the battery coolant radiator [59].

A more detailed analysis of the battery coolant radiator reveals that the heat from the coolant is transferred convectively to the channel wall and then either convectively to the cooling air or by conduction to the fin analogous to the cabin radiator. Heat is transferred convectively from the fin to the air. There are either planar or curved (fin) heat transfer surfaces [60].

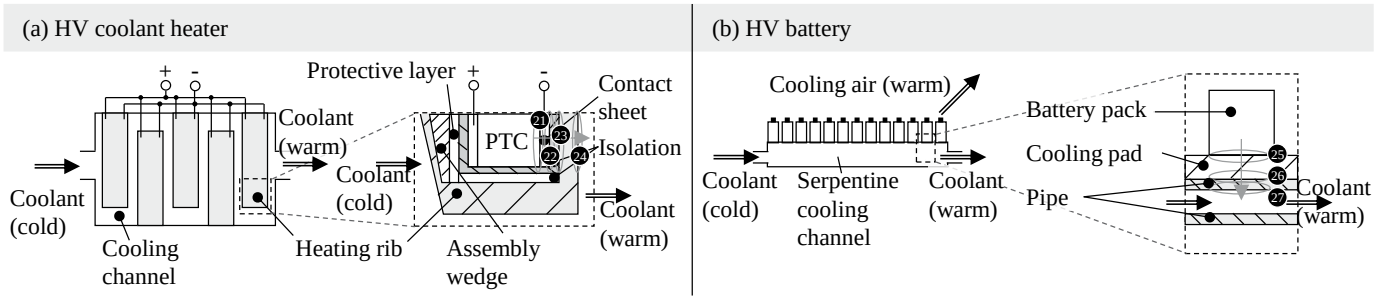


Figure A1. Heat transferring components in the battery coolant circuit, (**a**) HV coolant heater [58], (**b**) HV battery [59].

As displayed in Figure A1, within the low-temperature cooling circuit, the traction inverter is cooled by a heat sink with cooling channels. The heat in the multiple insulated-gate bipolar transistors (IGBT) is transferred to the heat sink through various layers (brazing layer, copper layer, ceramic, copper layer, brazing layer, copper base plate, and thermal interface material). All of these heat transfer surfaces are planar. The coolant flows through the finned heat sink and absorbs the heat convectively [61].

The low-temperature radiator [60] works analogous to the battery coolant radiator. Therefore, the structure will not be discussed again, but reference will be made to the battery coolant radiator.

The oil-coolant heat exchanger works in a similar way to the chiller, except that oil flows into the heat exchanger instead of the refrigerant. Heat is first transferred convectively from the oil to the wall surface, where it is conducted, and then transferred convectively from the wall surface to the coolant. All surfaces are planar and have a medium flowing through them [62].

The on-board AC/DC charger is water-cooled for efficient charging. The water-based coolant flows into the system, absorbs the heat from the electronic components, and then flows out again. The heat from the electronic components is conducted through a printed circuit board and a thermal interface material (e.g., thermal paste or silicone) to the aluminium heat sink. The heat sink forms cooling channels through which the cooling

medium is guided. Heat is transferred from the aluminium to the coolant by convection at the surfaces of the channels [63,64].

The DC/DC converter converts electric voltage from the HV (high voltage) to the LV (low voltage) level. For efficiency and performance reasons, the coolant is used to transfer heat from the electronic elements. For example, heat is generated in the transistor and conducted through various layers (see Figure A2) to the cooling element (thermal conduction between the layers). The water-filled cooling channels in the heat sink absorb the heat convectively via planar surfaces [65].

The air compressor is also integrated into the cooling circuit due to its high heat generation during air compression. In heavy-duty vehicle applications, a standard option is a water cooling of the cylinder head. The heat sink surrounds the inlet and outlet channels of the air, thus cooling the uncompressed and later compressed air. The heat generated by air compression is transferred convectively from the air to the channels of the heat sink. It is then transferred to the surfaces of the cooling channels of the component. There, convective heat exchange from the channel surfaces to the flowing coolant occurs [66].

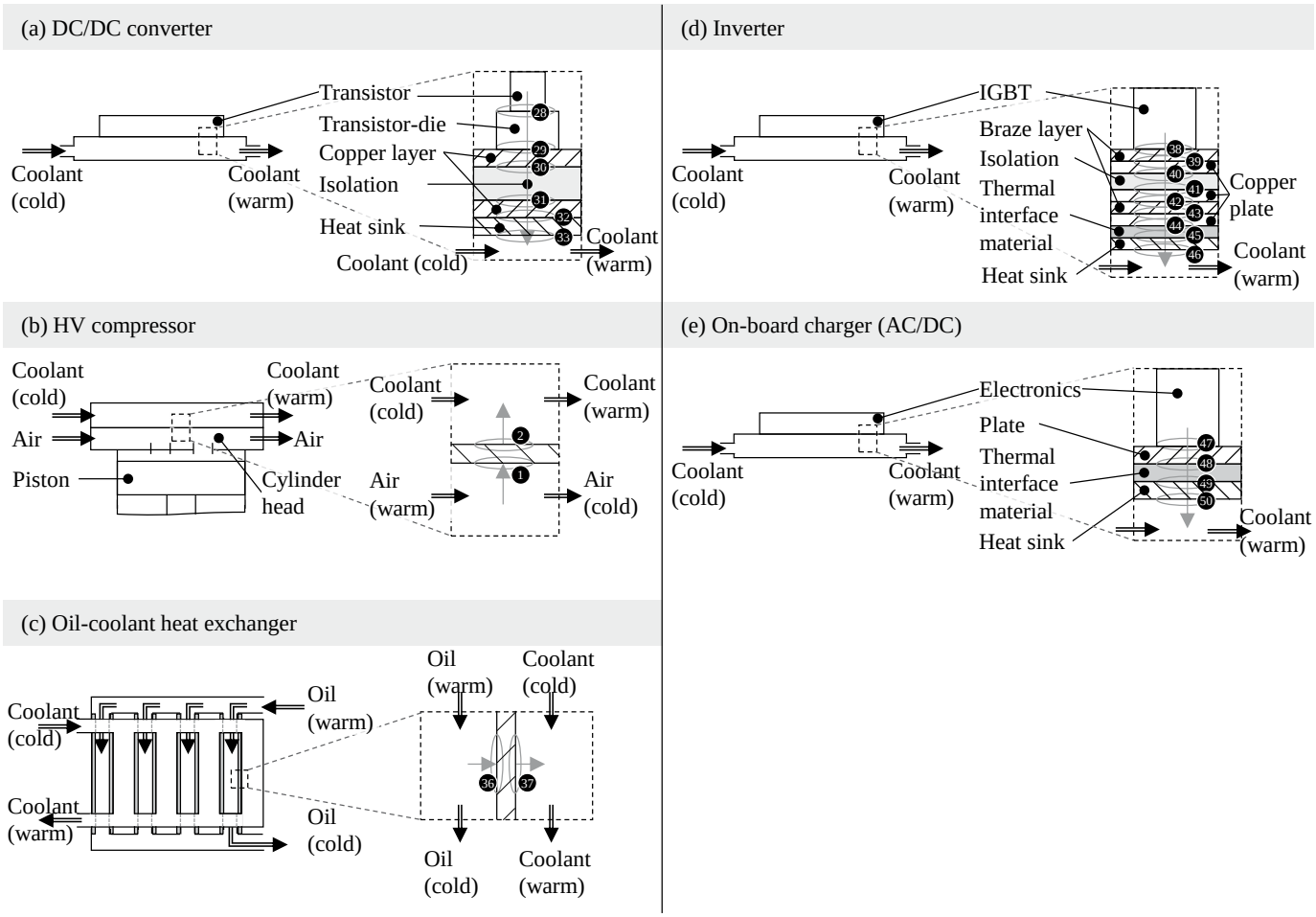


Figure A2. Heat transferring components in the low-temperature coolant circuit, (**a**) DC/DC converter [65], (**b**) HV compressor [66], (**c**) oil-coolant heat exchanger [62], (**d**) inverter [61], (**e**) on-board charger (AC/DC) [63,64].

Finally, the oil circuit is analysed in the following. As mentioned before, the electric motor introduced is oil-cooled (see Figure A3). One advantage is that the winding ends can be directly cooled, which is one of the main losses. As a result, higher continuous power can be achieved [67]. Oil enters the stator housing through channels and cools the stator

convectively through the cooling channels. The heat, which is mainly generated by the winding and iron losses within a winding, is then conductively transferred by contact with the electrical insulation and the stator groove [68]. Using guiding plates and structures, the oil is then directed to the rotor where it also convectively absorbs the rotor heat. Finally, the oil is removed from the lower part of the stator housing [44].

After the oil absorbs the heat from the electric motors, it is guided to the gearbox, for example via injection lubrication [69]. Alternatively, splash lubrication is possible for the electric truck drive system [70]. The heat generated by the tooth flank contact of the gears is transferred convectively to the oil that is in contact with the respective tooth flanks. The other rolling contacts, such as in bearings, are also lubricated and cooled by additional cooling channels. Heat transfer occurs in the same manner as described for the tooth contact. The oil is collected in the oil sump, where the heat is partly transferred convectively to the gearbox housing, conducted, and finally transferred convectively to the ambient air. However, the cooling of the oil is primarily conducted in the above-described oil-coolant heat exchanger.

It should be noted that the effect of thermal conduction within a component (structural element) is not included in the contact-based analysis. The reason for this is that according to the MBSE approach, it is not treated as a function, but as a property of the component/structure element.

All identified and derived thermal solution elements are listed in Table 6.

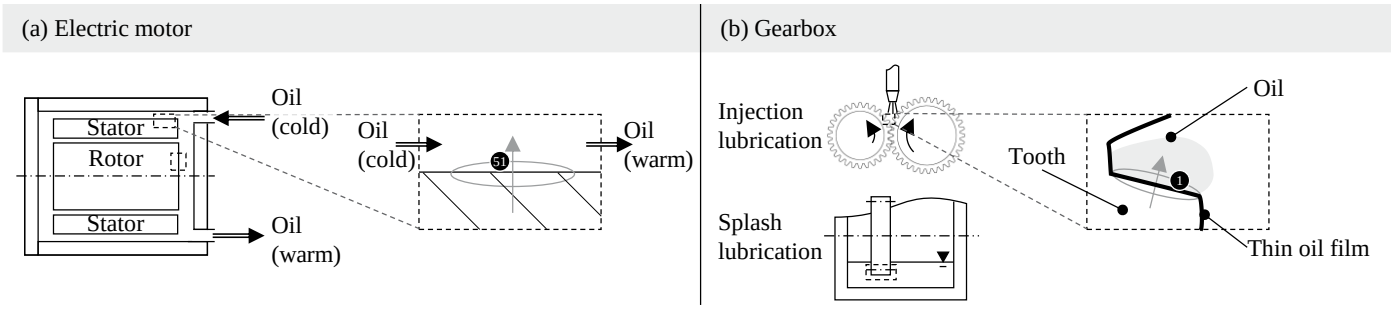


Figure A3. Heat transferring components in the oil circuit, (**a**) electric motor [44], (**b**) gearbox [69,71].

References

1. Gräßler, I.; Oleff, C. *Systems Engineering: Verstehen und Industriell Umsetzen*; Springer Vieweg: Berlin, Germany, 2022; ISBN 9783662645161.
2. *Systems Engineering for Automotive Powertrain Development*, 1st ed.; Hick, H., Küpper, K., Sorger, H., Eds.; Springer International Publishing: Cham, Germany, 2021; ISBN 9783319996295.
3. Feldhusen, J.; Grote, K.-H. *Pahl/Beitz Konstruktionslehre*; Springer: Berlin/Heidelberg, Germany, 2013.
4. Ehrlenspiel, K.; Meerkamm, H. *Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit*; Hanser: München, Germany, 2013; ISBN 3446435484.
5. Vajna, S.; Weber, C.; Zeman, K.; Hehenberger, P.; Gerhard, D.; Wartzack, S. *CAx Für Ingenieure: Eine praxisbezogene Einführung*, 2nd ed.; Springer: Berlin/Heidelberg, Germany, 2018; ISBN 366254623X.
6. Hussain, M.; Masoudi, N.; Mocko, G.; Paredis, C. Approaches for Simulation Model Reuse in Systems Design—A Review. In Proceedings of the WCX SAE World Congress Experience, Warrendale, PA, USA, 5 April 2022.
7. Jacobs, G.; Konrad, C.; Berroth, J.; Zerwas, T.; Höpfner, G.; Spütz, K. Function-Oriented Model-Based Product Development. In *Design Methodology for Future Products*; Krause, D., Heyden, E., Eds.; Springer: Cham, Germany, 2022; pp. 243–263. [CrossRef]
8. International Council on Systems Engineering. Systems Engineering Handbook. In *A Guide for Systems Life Cycle Processes and Activities Version 3.1*; International Council on Systems Engineering: San Diego, CA, USA, 2007.
9. Burton, B.A.; Aragon, R.W.; Bailey, S.A.; Koehler, K.D.; Mayes, L.A. The Reusable Software Library. *IEEE Softw.* **1987**, *4*, 25–33. [CrossRef]

10. Haber, A.; Ringert, J.O.; Rumpe, B. *Informationssysteme für die Angewandte Historische Geographie: Beiträge des Symposiums vom 20. März 1999 am Lehrstuhl für Informatik IV der RWTH Aachen*; Kulturlandschaft: Zeitschrift für Angewandte Historische Geographi: Regensburg, Germany, 1999; ISBN 0935-3232. Available online: http://aib.informatik.rwth-aachen.de/ (accessed on 17 February 2025).
11. Albers, A.; Heimicke, J.; Spadinger, M.; Reiss, N.; Breitschuh, J.; Richter, T.; Bursac, N.; Marthaler, F. A systematic approach to situation-adequate mechatronic system development by ASD—Agile Systems Design. *Procedia CIRP* **2019**, *84*, 1015–1022. [CrossRef]
12. Jagla, P.; Jacobs, G.; Spütz, K.; Berroth, J. Classification of function-oriented solution elements for MBSE. *Forsch. Ingenieurwes* **2023**, *87*, 469–477. [CrossRef]
13. Friedenthal, S.; Griego, R.; Sampson, M. INCOSE Model Based Systems Engineering (MBSE) Initiative. In Proceedings of the In INCOSE 2007 Symposium, San Diego, CA, USA, 24 June 2007.
14. Estefan, J. *Survey of Model-Based Systems Engineering (MBSE) Methodologies*; International Council on Systems Engineering: San Diego, CA, USA, 2008.
15. *ISO/IEC/IEEE 15288:2015*; Systems and Software Engineering—System Life Cycle Processes. International Organization for Standardization: Geneva, Switzerland, 2015.
16. Kruse, B.; Gilz, T.; Shea, K.; Eigner, M. Systematic Comparison of Functional Models in SysML for Design Library Evaluation. *Procedia CIRP* **2014**, *21*, 34–39. [CrossRef]
17. Gilz, T. *PLM-Integrated Interdisciplinary System Models in the Conceptual Design Phase Based on Model-Based Systems Engineering*; Technische Universität Kaiserslautern: Kaiserslautern, Germany, 2014; ISBN 978-3-941438-73-2.
18. Gausemeier, J.; Czaja, A.; Wiederkehr, O.; Dumitrescu, R.; Tschirner, C.; Steffen, D. Studie: Systems Engineering in der industriellen Praxis. *Tag Des Syst. Eng.* **2013**, 113–122. [CrossRef]
19. Hoepfner, G.; Kowalski, J.; Faustmann, C.; Zerwas, T.; Kranabitl, P.; Vafaei, S.; Jacobs, G.; Hick, H. A Classification Method for the Systematic Identification of Models and Workflows in MBSE. In Proceedings of the DS 119: 33rd Symposium Design for X (DFX2022), Hamburg, Germany, 22–23 September 2022; The Design Society: Glasgow, Scotland, 2022; p. 10.
20. VDI. *VDI-Richtlinie 2206: Entwicklung Mechatronischer und Cyber-Physischer Systeme*; Verein Deutscher Ingenieure: Harzgerode, Germany, 2021.
21. Alt, O. *Modellbasierte Systementwicklung mit SysML*; Carl Hanser Fachbuchverlag: München, Germany, 2012; ISBN 9783446431270.
22. Gausemeier, J.; Dorociak, R.; Pook, S.; Nyßen, A.; Terfloth, A. Computer-Aided Cross-Domain Modeling of Mechatronic Systems. In Proceedings of the DS 60: DESIGN 2010, the 11th International Design Conference, Dubrovnik, Croatia, 17–20 May 2010; pp. 723–732.
23. Moeser, G.; Kramer, C.; Grundel, M.; Neubert, M.; Kümpel, S.; Scheithauer, A.; Kleiner, S.; Albers, A. *Fortschrittsbericht zur Modellbasierten Unterstützung der Konstrukteurstätigkeit Durch FAS4M*; Carl Hanser Verlag: Munich, Germany, 2015; pp. 69–78. [CrossRef]
24. VDI. *Entwicklung Technischer Produkte und Systeme: Verein Deutscher Ingenieure, (2221 Blatt 1)*; Verein Deutscher Ingenieure: Harzgerode, Germany, 2019.
25. VDI. *Entwicklung Technischer Produkte und Systeme: Verein Deutscher Ingenieure, (2221 Blatt 2)*; Verein Deutscher Ingenieure: Harzgerode, Germany, 2019.
26. Zerwas, T.; Jacobs, G.; Spütz, K.; Höpfner, G.; Drave, I.; Berroth, J.; Guist, C.; Konrad, C.; Rumpe, B.; Kohl, J. Mechanical concept development using principle solution models. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1097*, 12001. [CrossRef]
27. Frank, U. *Spezifikationstechnik zur Beschreibung der Prinziplösung selbstoptimierender Systeme*; Heinz-Nixdorf-Inst: Paderborn, Germany, 2006; ISBN 978-3-935433-84-6.
28. Moeser, G. *Kurzversion FAS4M Methodenguideline: Methodisches Vorgehen im FAS4M-Ansatz*; Karlsruhe Institute for Technology: Karlsruhe, Germany, 2016.
29. Eigner, M.; Dickopf, T.; Schulte, T.; Schneider, M. *mecPro 2—Entwurf einer Beschreibungssystematik zur Entwicklung Cybertronischer Systeme mit SysML*; Carl Hanser Verlag: Munich, Germany, 2015; pp. 163–172. [CrossRef]
30. Albers, A.; Christian, Z. Interdisciplinary Systems Modeling Using the Contact & Channel-Model For Sysml. In Proceedings of the DS 68-9: 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Design Methods and Tools, Lyngby/Copenhagen, Denmark, 15–19 August 2011.
31. Hick, H.; Bajzek, M.; Faustmann, C. Definition of a system model for model-based development. *SN Appl. Sci.* **2019**, *1*, 15. [CrossRef]
32. Faustmann, C.; Bajzek, M.; Hick, H.; Edtmayer, J.; Walch, S. System models and model classification in tribological system development. *Syst. Eng.* **2020**, *23*, 783–794. [CrossRef]
33. Höpfner, G.; Jacobs, G.; Zerwas, T.; Drave, I.; Berroth, J.; Guist, C.; Rumpe, B.; Kohl, J. Model-Based Design Workflows for Cyber-Physical Systems Applied to an Electric-Mechanical Coolant Pump. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2021; Volume 1097, p. 12004. [CrossRef]

34. Koller, R.; Kastrup, N. *Prinziplösungen zur Konstruktion Technischer Produkte*; Springer: Berlin, Germany; New York, NY, USA, 1994; ISBN 3-540-58243-6.
35. Spütz, K.; Berges, J.; Jacobs, G.; Berroth, J.; Konrad, C. Classification of Simulation Models for the Model-based Design of Plastic-Metal Hybrid Joints. *Procedia CIRP* **2022**, *109*, 37–42. [CrossRef]
36. *DIN 32705*; Klassifikationssysteme–Erstellung und Weiterentwicklung von Klassifikationssystemen. Deutsches Insitut für Normung: Berlin, Germany, 2021.
37. Rodenacker, W.G. *Methodisches Konstruieren: Grundlagen, Methodik, Praktische Beispiele*, 4th ed.; Springer: Berlin, Germany, 1991; ISBN 9783540539773.
38. Tschöke, H.; Gutzmer, P.; Pfund, T. *Elektrifizierung des Antriebsstrangs*; Springer: Berlin/Heidelberg, Germany, 2019.
39. Wagner, W. *Wärmeaustauscher: Grundlagen, Aufbau und Funktion Thermischer Apparate*; Vogel Business Media: Würzburg, Germany, 2015; ISBN 9783834333612.
40. Wagner, W. *Wärmeübertragung: Grundlagen*; Vogel Buchverlag: Würzburg, Germany, 2011; ISBN 3834332097.
41. Böckh, P.; von Wetzel, T. *Wärmeübertragung: Grundlagen und Praxis*; Springer Vieweg: Berlin/Heidelberg, Germany, 2015; ISBN 3662444763.
42. Sigloch, H. *Technische Fluidmechanik, 11. Auflage*; Springer: Berlin/Heidelberg, Germany, 2022; ISBN 9783662646281.
43. Art, L.; Jung, M.; Lutz, R. Thermomanagementsysteme für elektrifizierte Nutzfahrzeuge. *MTZ Mot. Z.* **2022**, *83*, 62–67. [CrossRef]
44. Swales, S.H.; Turnbull, P.F.; Schulze, B.; Poskie, F.R.; Omell, W.J.; Deneszczuk, W.C. Ölgekühlter Motor/Generator für einen Kraftfahrzeugantriebsstrang. DE20101047507 20101005, 5 October 2010.
45. Weustenfeld, T. Heiz- und Kühlkonzept für Ein Batterieelektrisches Fahrzeug Basierend auf Sekundärkreisläufen. Ph.D. Thesis, Technische Universität Braunschweig, Braunschweig, Germany, 2017.
46. Kamoshida, O.; Higashiyama, N.; Takagi, M.; Hirayama, T. EVAPORATOR. US201815963998 20180426, 26 April 2018.
47. Foerster, U.D.I.F. Kraftfahrzeugklimaanlage. DE20101043000 20101027, 27 October 2010.
48. Wesner, M.; Herrmann, H.G.; Klein, P.; Himmer, T. Heat Exchanger. US201213979473 20120113, 13 January 2012.
49. Hoerte, T. A Plate Heat Exchanger. EP20040809149 20041222, 22 December 2004.
50. Bohlender, F.; Niederer, M.; Morgen, C. Electric Heating Device, in Particular for a Motor Vehicle. EP20110010087 20111222, 22 December 2011.
51. Molt, K. BF03221507 // PTC-Heizung. *ATZ Automob. Z.* **1998**, *100*, 496–500. [CrossRef]
52. Kohl, M.; Walter, C.; Schernikau, J. Heizeinrichtung für ein Kraftfahrzeug. DE201310215180 20130801, 1 August 2013.
53. Molt, K.D.I. Radiator for a Motor Vehicle. EP19930117850 19931104, 4 November 1993.
54. Moers, F.; Jacobs, G.; Mennicken, M.; Irnich, L.; Boelsen, K.; Höpfner, G. Reusable solution element libraries for accelerated application of MBSE in mechanical product development. *Forsch. Ingenieurwes* **2025**, *89*, 54. [CrossRef]
55. Cattani, L.; Malavasi, M.; Bozzoli, F.; D'Alessandro, V.; Giammichele, L. Experimental Analysis of an Innovative Electrical Battery Thermal Management System. *Energies* **2023**, *16*, 5071. [CrossRef]
56. Stubkier, S.I.; Østergaard, J.A.; Nielsen, C.R. A Wind Turbine Comprising a Liquid Cooler and a Method for Cooling a Liquid. WO2023EP53272 20230210, 10 February 2023.
57. Airoldi, G. Inclined Heat Exchanger for a Wind Turbine. EP20190151213 20190110, 10 January 2019.
58. Bohlender, F.; Schwarzer, A.; Niederer, M. Electric Heating Device. EP20170155418 20170209, 9 February 2017.
59. Li, M.; Wang, J.; Guo, Q.; Li, Y.; Xue, Q.; Qin, G. Numerical Analysis of Cooling Plates with Different Structures for Electric Vehicle Battery Thermal Management Systems. *J. Energy Eng.* **2020**, *146*, 4020037. [CrossRef]
60. Schicht, H.; Gieras, M.; Huisman, M. Device for Protecting the Radiator of a Motor Vehicle Against Projected Particles. EP19980925538 19980506, 6 May 1998.
61. Doppelbauer, M. *Grundlagen der Elektromobilität: Technik, Praxis, Energie und Umwelt*; Springer Vieweg: Wiesbaden/Heidelberg, Germany, 2020; ISBN 9783658297299.
62. Brost, V.; Kalbacher, K.; Kaesinger, R. Plate Heat Exchanger. EP19960105405 19960404, 4 April 1996.
63. Dini, P.; Saponara, S. Electro-Thermal Model-Based Design of Bidirectional On-Board Chargers in Hybrid and Full Electric Vehicles. *Electronics* **2022**, *11*, 112. [CrossRef]
64. Tayyara, O.; Da Silva, C.; Nasr, M.; Assadi, A.; Gupta, K.; Trescases, O.; Amon, C.H. Electro-Thermal Codesign Methodology of an On-Board Electric Vehicle Charger. *J. Electron. Packag.* **2020**, *142*, 041102. [CrossRef]
65. Wituski, J.; Kleimaier, A. *GaN Leistungsmodul mit IMS Substrat für eine 3-LevelFlying-Capacitorschaltung an 800 V DC*; Hochschule für Angewandte Wissenschaften Landshut: Landshut, Germany, 2023.
66. Hofstetter, T. Air Compressor for a Compressed Air System, in Particular for a Compressed Air Brake System for a Commercial Vehicle. EP20130005925 20131219, 19 December 2013.
67. Lehmann, R.; Künzler, M.; Moullion, M.; Gauterin, F. Comparison of Commonly Used Cooling Concepts for Electrical Machines in Automotive Applications. *Machines* **2022**, *10*, 442. [CrossRef]

68. Bauer, D. *Verlustanalyse bei Elektrischen Maschinen für Elektro-und Hybridfahrzeuge zur Weiterverarbeitung in Thermischen Netzwerkmodellen*; Springer: Wiesbaden, Germany, 2019; ISBN 978-3-658-24271-8.
69. Wang, Y.; Niu, W.; Chen, Y.; Song, G.; Tang, W. Convection heat transfer and temperature analysis of oil jet lubricated spur gears. *Ind. Lubr. Tribol.* **2016**, *68*, 624–631. [CrossRef]
70. Niemann, G.; Winter, H. *Maschinenelemente: Band 2: Getriebe Allgemein, Zahnradgetriebe—Grundlagen, Stirnradgetriebe, Zweite, Völlig Neubearbeitete Auflage*; Springer: Berlin/Heidelberg, Germany, 2003; ISBN 978-3-662-11874-0.
71. Czichos, H.; Habig, K.-H. *Tribologie-Handbuch: Tribometrie, Tribomaterialien, Tribotechnik*; Springer: Wiesbaden, Germany, 2010; ISBN 978-3-8348-0017-6.

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