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Tailoring the V-Model for Optics: A Methodology for Optomechatronic Systems

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Abstract: The integration of optical technologies into once purely mechatronic systems enables innovative functions, but simultaneously increases the complexity of previous mechatronic system development. Therefore, a process has been elaborated to develop these so-called optomechatronic systems by Knöchelmann at the Institute of Product Development at Leibniz University Hanover, which is based on the V-Model of VDI 2206 and can be applied to various fields of application. For a target-oriented development in a specific product context and for systems with competing main requirements, detailing and adapting the process is recommended. High-resolution lighting systems are one of them, where requirements for high optical efficiency and image quality lead to a conflict of objectives. Focusing on the optics domain, Ley elaborated methods for the preliminary and detailed design of high-resolution lighting systems to address the aforementioned conflict of objectives. This contribution focuses on the integration of Ley's design methods into Knöchelmann's process model within the phases of system design and domain-specific design, allowing us to analyze the impact of the system design on the fulfillment of main requirements to achieve an optimal solution of the conflict of objectives. To illustrate this, the integrated process model is described using an example from automotive lighting technology.

Keywords: optomechatronics; development methodologies; V-model; optics design; high-resolution lighting systems

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1. Introduction

1.1. Motivation

Based on mechatronics, optomechatronics describes the engineering discipline in which optical, mechanical, electronic and information-processing components interact by means of optical radiation to achieve a specific realization of different functions [1–3]. According to [4], optomechatronic systems can have the main functions shown in Figure 1 or combine several of these functions. For example, the main function "Measure" is used in the field of biomedical engineering in optical coherence tomography (OCT) and dermoscopy [5,6]. In systems used for visible light communication, for example, the main functions "Illuminate" and "Data transfer" are combined [7,8].

For successful integration of optical, mechanical, electronic and information-processing components, a methodical approach is recommended, as with mechatronic systems, in which the specific challenges of the technology and product context are taken into account. For this purpose, Knöchelmann presents in [9] a generic process model based on the V-Model of VDI guideline 2206 [10]. With regard to optomechatronic systems, particularly challenging developments are those in which the basic functions shown in Figure 1 interact.

Competing and partly contradictory requirements have an influence on the development in these cases and require detailing of the generic process from Knöchelmann.

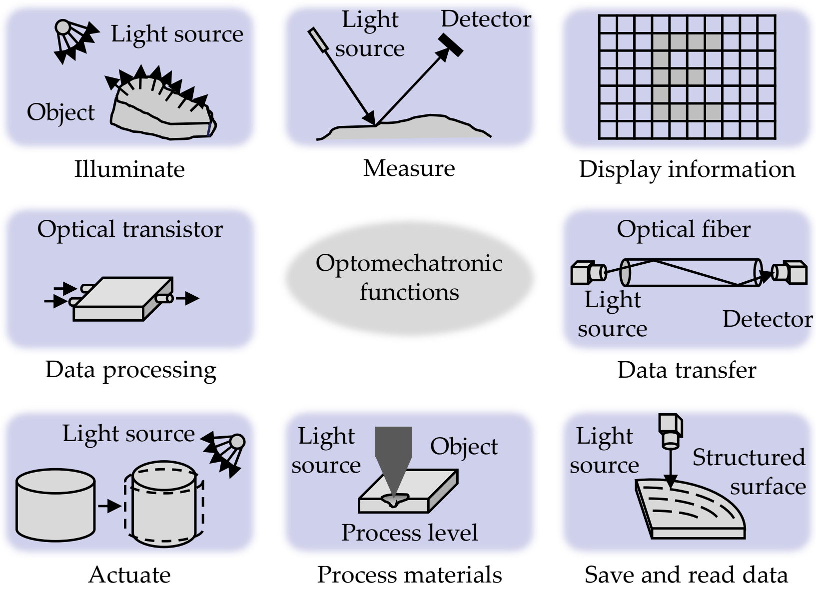

Figure 1. Basic functions of optomechatronic systems according to [4].

Therefore, the motivation of this contribution is to elaborate this detailing and to show how it can be performed for the specific application area of high-resolution lighting systems. Such systems are, for instance, used in video projectors and recently also in vehicle headlamps [11].

In several innovation projects, the technological potentials of high-resolution lighting systems have been analyzed at the Institute of Product Development at Leibniz University Hanover by means of prototypes [12–15]. Based on these innovation projects, Ley derived in [16,17] specific design methods for the preliminary and detailed design of high-resolution lighting systems. With these practical development experiences and elaborated design methods, the authors contribute to this field and show how the generic process to develop optomechatronic systems of [9] can be detailed.

We show how the specific methods of [16,17] can be linked with the general framework of [9] to obtain a methodical development approach for high-resolution lighting systems. To illustrate the presented approach, the development of a high-resolution headlamp is described as an application example. In the case of high-resolution lighting systems, the specific requirements arising from the basic functions "Display information" and "Illuminate" lead to a conflict of objectives between high optical efficiency and high imaging quality of the system [12].

1.2. Introduction of the Application Example

An important prerequisite for safe road traffic at night and twilight is optimal illumination of the traffic area without dazzling other road users. Technological advances in ambient sensor technology enable the realization of new safety and comfort functions in the field of vehicle lighting by detecting vehicles and pedestrians [18].

If so-called light modulators are used in the optical path of headlamps, the light distribution can be modulated in individual areas or completely and thus adapted to the current ambient conditions. One function already implemented in the mass segment is glare-free high beam, in which other road users are detected by analyzing the vehicle camera image. Subsequently, the luminous intensity of the high beam in this direction is reduced to such an extent that glare is avoided [19].

By controlling headlamps pixel wise, which is comparable to the image generation of video projectors, additionally, completely new functions can be implemented. With knowledge of the exact geometric conditions, the light distribution of a high-resolution headlamp can be modulated to create visible projections on the road in front of the vehicle [20–23]. With this technological possibility, a variety of functional ideas arise, such as an extension of the driver-vehicle interface to display information or projections to communicate with other road users [24,25]. A specific example of a projection function is the so-called construction site light. Here, by displaying the real vehicle width on the road, the driver is verifiably enabled to guide the vehicle in narrow places more easily than without the projection function [21,23,26].

Different optical concepts and technologies for image modulation can be considered to develop high-resolution vehicle headlamps [15,27]. With the objective of evaluating the potential of Digital Micromirror Arrays (DMDs) for image modulation in high-resolution vehicle headlamps, various research projects have been carried out at the Institute of Product Development, which are part of the application example in this contribution. A DMD consists of hundreds of thousands to several million individually controllable micromirrors. Depending on the micromirror position, the light focused onto the DMD by the illumination optics is reflected either onto an absorber or into the subsystem for projection into the field of view. Using the projection subsystem, the image modulated by the DMD is projected onto the road so that each micromirror becomes a pixel of the projected image. Due to the reflection-based operating principle of DMDs, an overlap of the light paths for illumination and projection results in a short distance in front of the DMD. To achieve sufficient separation of the two light paths, different system architectures are suitable [28–30]. One solution, as shown in Figure 2, is to implement a telecentric system architecture using a so-called total internal reflection (TIR) prism, which exploits the phenomenon of total internal reflection.

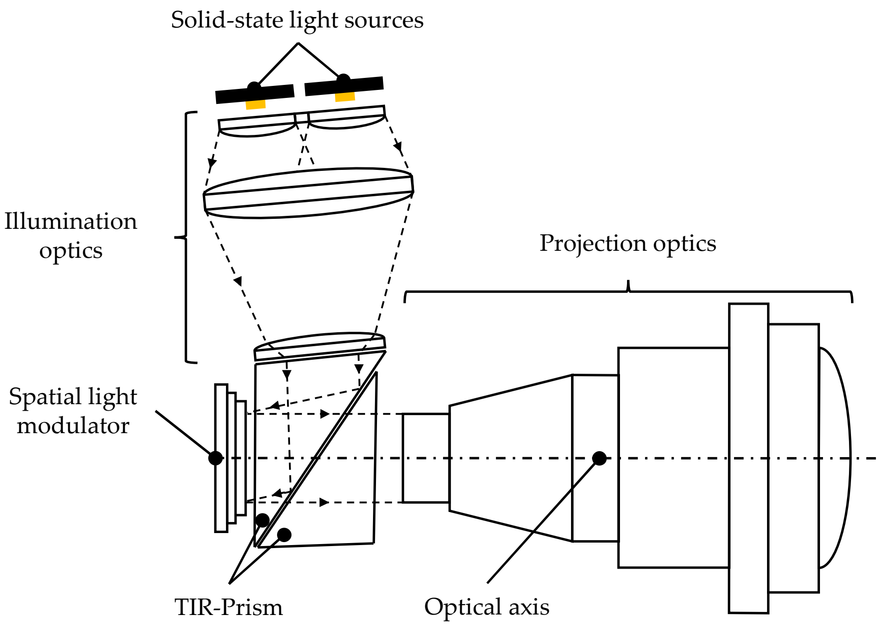

Figure 2. Concept of a high-resolution headlamp according to [31].

In particular, the challenges outlined in Figure 3 can be derived for a high-resolution lighting system, which must be taken into account in the further development process [16,22].

- **Efficiency:** High-resolution lighting systems for vehicle front lighting require not only high optical efficiency but also high electrical efficiency, so semiconductor light sources such as LEDs and laser diodes are increasingly being used to generate light. However, compared to conventional light sources, semiconductor light sources differ significantly in terms of operation, radiation characteristics and thermal management [32–34].

- **Image quality:** In optical systems, effects such as diffraction, aberration or distortion, which influence the image quality, have to be taken into account. Various measures can be implemented to correct these effects; for example, the combination of several lenses made of different materials. However, since losses occur at each optical element as a result of Fresnel reflections and material defects, which have a negative impact on the optical efficiency of the system, the use of as few optical elements as possible is advantageous. Consequently, a conflict of objectives arises between optical efficiency and image quality of the system [35,36].
- **Light modulation:** So-called light modulators such as liquid crystal displays (e.g., LCD, LCoS) or digital micromirror arrays are used to generate high resolutions. LED matrices represent another way to develop active lighting systems, but are not in the focus of this contribution due to the significantly lower achievable resolution. While the aforementioned technologies are well established in the field of video projection applications, their deployment in the field of vehicle front lighting is new. When using a DMD, the limited tilt angle of the micromirrors constrains the aperture angle of the incident light beam, which thus limits the maximum luminous flux that can be modulated. The operation of liquid crystal displays is based on the use of polarized light, which results in special requirements for the light source and the use of special optical elements for polarization [37,38].

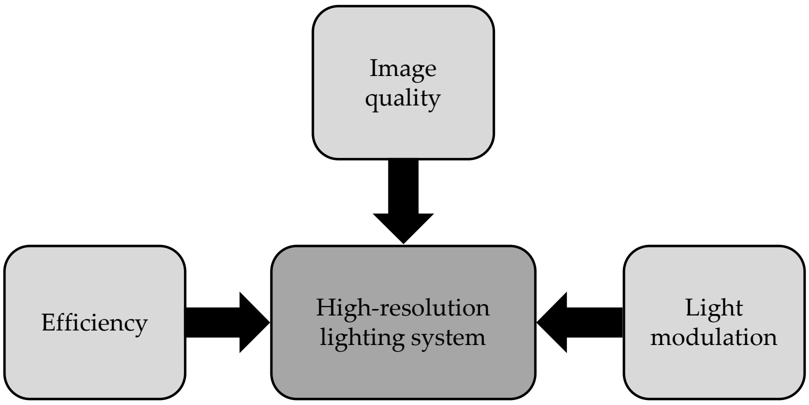

Figure 3. Challenges in the development of high-resolution lighting systems.

Based on the challenges presented, it is obvious that a methodical approach is required for the targeted development of high-resolution lighting systems. The following sections of this paper will therefore explain how the challenges involved in the development of high-resolution lighting systems can be met by concretizing the V-Model (cf. Section 1.1) to develop optomechatronic systems. For this purpose, Section 2 describes the process for the development of optomechatronic systems by Knöchelmann and the underlying V-Model [9]. Based on this, in Section 3 it is explained how the method for the preliminary design of high-resolution lighting systems presented in [16] by Ley can be integrated into the process phase for the system design of optomechatronic systems according to [9] by Knöchelmann. This is followed by the integration of the method introduced in [17] by Ley for the detailed design of high-resolution lighting systems into the process phase for the domain-specific design of optomechatronic systems according to [9] by Knöchelmann. Finally, the variant of the V-Model for high-resolution lighting systems elaborated in this contribution is discussed on the basis of application examples in Section 4.

2. V-Model to Develop Optomechatronic Systems

The V-model to develop optomechatronic systems is based on the general V-model to develop mechatronic systems. Therefore, in this section, the V-model in the version of VDI guideline 2206 is first introduced as a basis. Subsequently, requirements are derived which have to be fulfilled by an adapted V-model to develop optomechatronic systems. Based on this, the process model elaborated by Knöchelmann in [9] is described.

VDI guideline 2206 describes a procedure to develop mechatronic systems [10]. In the 2021 updated version of the guideline, this area of application is extended from mechatronic to cyber-physical mechatronic systems [39,40]. Figure 4 shows the basic procedure. Based on a consistent requirements management, the interaction between the individual domains is designed in the system design where all cross-domain interfaces are defined. The domain-specific subsystems and components are designed in the phase of domain-specific design and then assembled in the phase of system integration. Systematic verification after each integration step ensures that the functional properties meet the previously defined requirements.

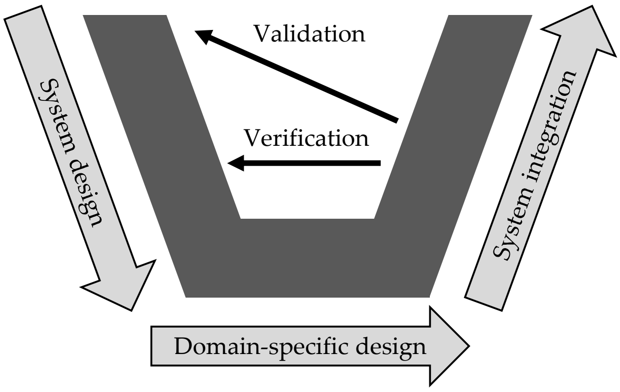

Figure 4. Simplified illustration of the V-Model according to [10].

The guideline is applied to systems composed of mechanical and electronic components. By integrating information technology components, mechatronic and cyber-physical functions can be implemented. If optical components are used in addition to the mechanical and electronic ones, specific challenges must be addressed during development. Hence the requirements for the development process are summarized below according to [9].

- **Applicability for system developments:** Optomechatronic systems consist of components of the domains mechanics, electronics, infomation technology and optics. To achieve the specified functional behavior, the focus is particularly on interfaces and interactions between the domains and components of the system [41].
- **Linking process elements of micro- and macrology:** Within the phases system design, domain-specific design and system integration, the V-Model presented earlier contains three superordinate sections that allow a development project to be classified into work packages and milestones. Lindemann [42] describes this view of a process as macrology. Furthermore, the applicability of a process depends on the definition of tangible work steps that can be assigned to the micrology. The V-Model of VDI guideline 2206 contains detailed work steps for the phases mentioned in order to provide developers with additional orientation [10]. Linking elements of macro- and micrology therefore helps in the development of complex systems and is required for the process to develop optomechatronic systems.
- **Consideration of the concept-defining requirements of the optics domain:** Changes made in a late phase of system development are associated with high effort and risk. In development methodology, it is therefore recommended that requirements which have a high influence on the system concept in particular be taken into account early in the development process [43]. In the optomechatronic systems discussed in this contribution, the functions “Illuminate” and “Display information” (cf. Figure 1) are the focus of the conceptual consideration. The requirements for the optical function should therefore be analyzed particularly early in the development process and implemented in a solution concept.
- **Consideration of effects on humans:** Effects on humans are a particular focus for illuminating optical systems. As part of the main function, those effects can be intended and part of the development goal, but they can also imply an unwanted

disturbing effect. A further requirement for the development process is therefore the explicit consideration of the interactions of the system with humans.

In addition to the V-Model of VDI guideline 2206 already described, there are other process models derived from the original V-Model that are structured similarly. The models are evaluated in Table 1 on the basis of the requirements described above.

The process model of VDI guideline 2206 is primarily used to develop mechatronic systems where interdisciplinary challenges are in the foreground [10]. The model is made applicable by specific process phases. In addition, it is recommended to further detail the model for specific development tasks. The second requirement of linking elements of micro- and macrology can therefore be regarded as only partially fulfilled.

The V-Model in Model-Based-Systems-Engineering (MBSE) focuses on the continuous simulation of the individual system components. Furthermore, processes that are upstream and downstream of the V-Model are recorded in the model. However, a link to elements of the micrology for the detailed description of work packages is not included [44].

V-Model XT was developed with the objective of achieving a high degree of adaptability for military and infrastructure projects [45]. Unlike the models presented so far, the V-Model XT is implemented in a software tool. The basic principles of the V-Model correspond to those of the general procedure of VDI guideline 2206.

For tangible development tasks, there are other adapted V-Models such as the models according to [46–49]. These models focus on applicability through concrete work steps. However, concept-determining optical properties and the effect on humans are not considered.

Table 1. Evaluation of interdisciplinary development processes based on the imposed requirements. fulfilled (+), partially fulfilled (o), not fulfilled (-) according to [9].

	V-Model VDI2206	V-Model MBSE	V-Model XT	Adjusted V-Models *
Applicability for system developments	+	+	+	+
Linking between process elements of micrologic and macrologic	o	-	o	+
Consideration of the concept-defining requirements of the optics domain	-	-	-	-
Consideration of effects on humans	-	-	-	-

* according to [46–49].

Based on the analysis shown, Knöchelmann derives in [9] that the V-Model of VDI guideline 2206 is a suitable basis for the development process of optomechatronic systems. The possible linking of the general model with elements of micrology is successfully implemented by [46–49] to detail the V-Model for tangible development tasks. Figure 5 shows the process to develop optomechatronic systems elaborated in [9] by Knöchelmann. In the following, the process is presented and the requirements described and how they are taken into account are shown.

The process is divided into the phases requirements analysis (1); system design (2); domain-specific design (3); and system integration (4). The final property validation (5) is performed with the overall system in the field. The basic structure of the process model with five phases for systematic decomposition, integration and property validation at different integration levels is based on the general V-Model of VDI guideline 2206. The process is therefore suitable for system developments with elements from different domains. To increase the applicability of the process, a process phase is defined for each of the phases mentioned. Each process phase is assigned several work steps, which are described in detail. The concept-defining properties of the optics domain should be taken into account early in the development process in order to avoid time-consuming changes later in the development process. Therefore, a first preliminary design of the optical system is recommended already in the system design phase (2). In Figure 5, this is represented by starting the design of optical components already in phase 2 (development of subsystems).

In the general V-Model, on the other hand, all domains are considered equal in the phase of the system design. The outcome of the system design is a cross-domain solution concept, which serves as the basis for the domain-specific design (3).

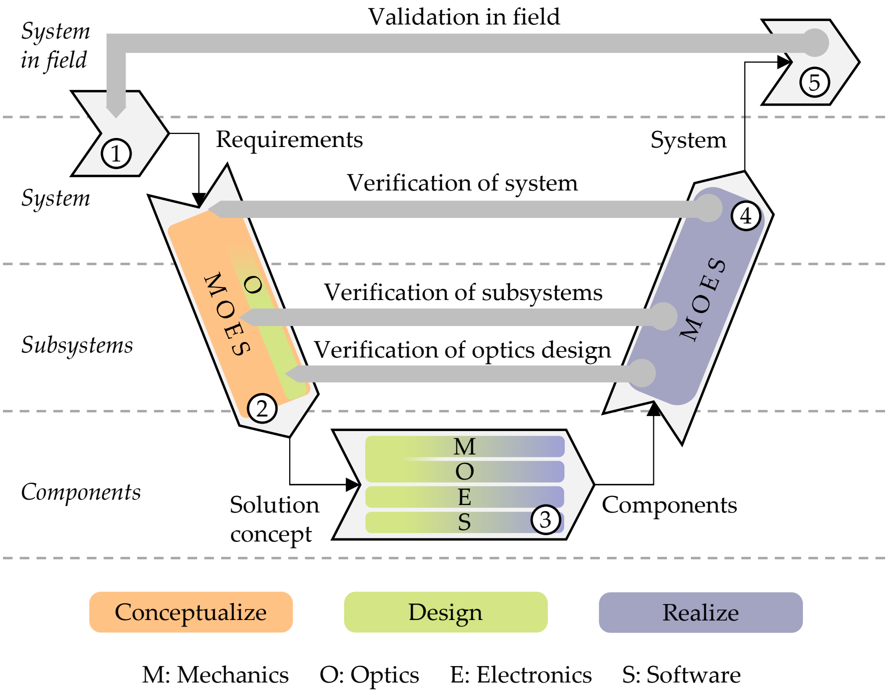

Figure 5. V-Model to develop optomechatronic systems according to [9].

Contrary to what is recommended in the general V-Model, the development of optomechatronic systems cannot be carried out completely separately in the individual domains. In particular, interactions between the domains optics and mechanics, as they occur for example at mechanical mounts of the optical elements having an influence on the image quality and scattering effects, must be taken into account in this phase. This is indicated in the process (cf. Figure 5) at the beginning of the domain-specific design by the overlap of the optics (O) and mechanics (M) domains. The domain-specific design is followed by the production and procurement of the individual components and the realization of the software, so that all elements of the system are available as actual components at the end of phase (3). In the system integration phase, these are assembled and their function is validated by integration tests. The first step is to verify the function of the optical components that have been defined as determining the concept. Progressively integrating additional components, their interaction is validated and aligned with the definition of the subsystems from phase (2). The general V-Model ends with this phase. For optomechatronic systems, it is also recommended to perform a property validation of the overall system in the field (5), in particular to take into account the effects of the system on humans under realistic environmental influences.

3. Concretization of the V-Model for High Resolution Lighting Systems

In the following, we present a concretization of the V-model for optomechatronic systems from Section 2 for high-resolution lighting systems. For this purpose, Section 3.1 extends the process phase for system design by the method for the preliminary design of high-resolution lighting systems elaborated by Ley in [16] and describes the individual steps in terms of approaches and results. Due to dependencies of the domains optics and mechanics, specific challenges also emerge in context of the domain-specific design of high-resolution lighting systems (cf. Section 1.2). For this reason, in Section 3.2 the domain optics within the process phase for the domain-specific design of optomechatronic systems is concretized by the method from [17] for the sequential and non-sequential detailed design of high-resolution lighting systems. First, the individual process steps are explained and then the approaches and results of the method are presented. In the last Section 3.3, the process phase for system integration and property validation is described, in which the components are integrated into subsystems and these are further integrated into an overall system and each verified against the requirements.

3.1. Extension of the System Design Process Phase to Include the Method for the Preliminary Design of High-Resolution Lighting Systems

Within the phase of system design, the objective is to develop a cross-domain solution concept that achieves the previously defined requirements for the system. In this context, as in general design theory, the specification of physical and logical system components and their relations to each other are considered part of the solution concept [43]. In the process to develop optomechatronic systems, the sequence and naming of the work steps are taken from VDI guideline 2206 and their content is adapted (cf. Figure 6, left).

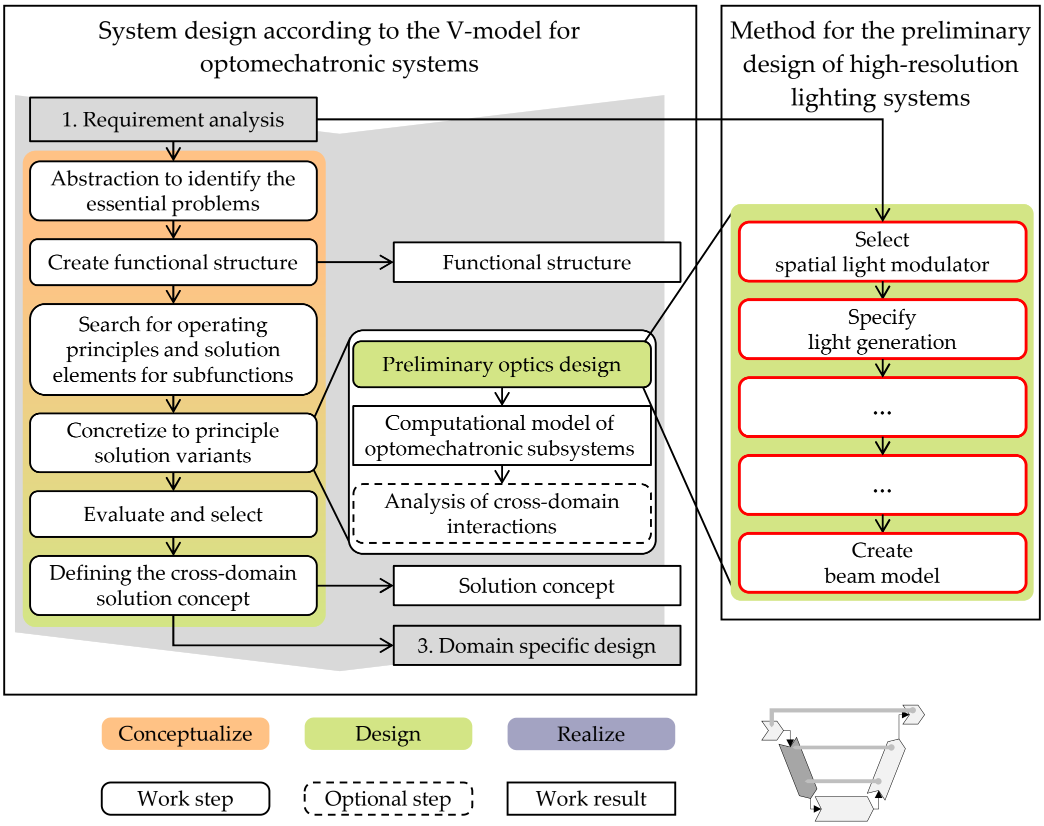

Figure 6. Process phase for the system design of optomechatronic systems according to [9] extended by the method for the preliminary design of high-resolution lighting systems according to [16]; The dark grey box in the pictogram of the V-Model in the lower right serves as orientation which process phase is observed.

First, the development goal is abstracted in order to derive cross-domain requirements (1) and identify essential problems. Then, with the objective of establishing a cross-domain functional structure, all main functions (cf. Section 1.1) of the system are specified and divided into sub-functions and minor functions. In order to fulfill the subfunctions, operating principles and solution elements are subsequently searched for and selected. The next step, "Concretize to principle solution variants", plays an important role in the system design of optomechatronic systems, since according to Knöchelmann, a first preliminary design of the optical system is already recommended in this step [9]. The developer is free to choose the approach for this task. For high-resolution lighting systems considered in this contribution, it is recommended that a specific and application-oriented description of the approach be used for development. The method described in [16] by Ley for the preliminary design of high-resolution lighting systems helps the developer to identify the central conflicts of objectives and dependencies in the optical path of these systems and to influence them in a targeted manner.

In order to meet the challenges described in Section 1 to develop high-resolution lighting systems, it is therefore recommended to subdivide the process step "Preliminary optics design" into further steps as part of the concretization into principle solution variants (Figure 6, right). In the literature, different methods are provided for the preliminary design of optical systems [50–54]. However, all methods have in common that they are unsuitable for the preliminary design of high-resolution lighting systems [17]. This is predominantly due to the fact that, in addition to specific design steps arising from the challenges mentioned in Section 1.2, the Étendue must also be considered a conservation quantity.

The Étendue can be used to describe the spatial and angular propagation of light through an optical system [55]. Within an ideal optical system, the Étendue can be preserved. However, due to diffusion, scattering, aberration and diffraction at imperfect optical elements, the Étendue increases under real conditions [56]. A lossless reduction of the Étendue is not possible. Furthermore, in each optical system there exists an element with the lowest Étendue, which thus limits the light propagation. With this knowledge, statements can be made about the theoretical maximum efficiency of optical systems. Since the spatial light modulator is usually the Étendue-limiting element in high-resolution lighting systems, the first step is to select the light modulator for the preliminary design. Based on the Étendue of the selected light modulator, the light generation must then be specified. If another component has the lowest Étendue, this element must be considered accordingly. Taking into account functional dependencies between the subsystem to illuminate the light modulator and to project it into the traffic area (see Section 1.2), the system architecture is determined by positioning the two subsystems with respect to each other. In the subsequent design steps "Define illumination strategy" and "Adjust distortion", the conflict of objectives between high optical efficiency and image quality is analyzed on the basis of the system architecture. Since different solution principles to implement high-resolution lighting systems are possible in each design step, the preliminary designs are checked using a so-called Étendue factor and a luminous flux factor. The luminous flux factor is used to check the preliminary design with regard to the fulfillment of the photometric requirements, and the Étendue factor is used to evaluate the efficiency (cf. Figure 7). Finally, a beam model of the optical path is created, which serves as the basis for the detailed design, which is carried out within the framework of the domain-specific design.

- **Select spatial light modulator:** For the preliminary design of a high-resolution lighting system, we first need to define the Étendule-limiting component, which in this case is the light modulator. If no specific technology for light modulation (e.g., LCD or DMD) has been defined within the scope of the requirements elicitation; this is carried out in this step. Criteria for selecting a suitable technology may include resolution, contrast or efficiency. Furthermore, the aspect ratio and the number of light modulators to be used must be defined. Based on the luminous flux in the light distribution to be generated and an initially assumed efficiency of the subsystem used for projection into the traffic area, the minimum required Étendue of the light modulator can be determined. Since the functional principle of the modulator determines its acceptance angle, the active area required for modulation can be determined accordingly.
- **Specify light generation:** For the illumination of the active area of the selected light modulator, a suitable technology for light generation (discharge lamp, electroluminescent emitter, etc.) has to be specified, if not already done in the requirements elicitation. Then, based on the Étendue of the light modulator, the number of light sources to be used and the size of the emission areas need to be determined. Neglecting Fresnel reflections and scattering in the optical system, an efficient light system can be assumed if the Étendue of light source and light modulator are equivalent.

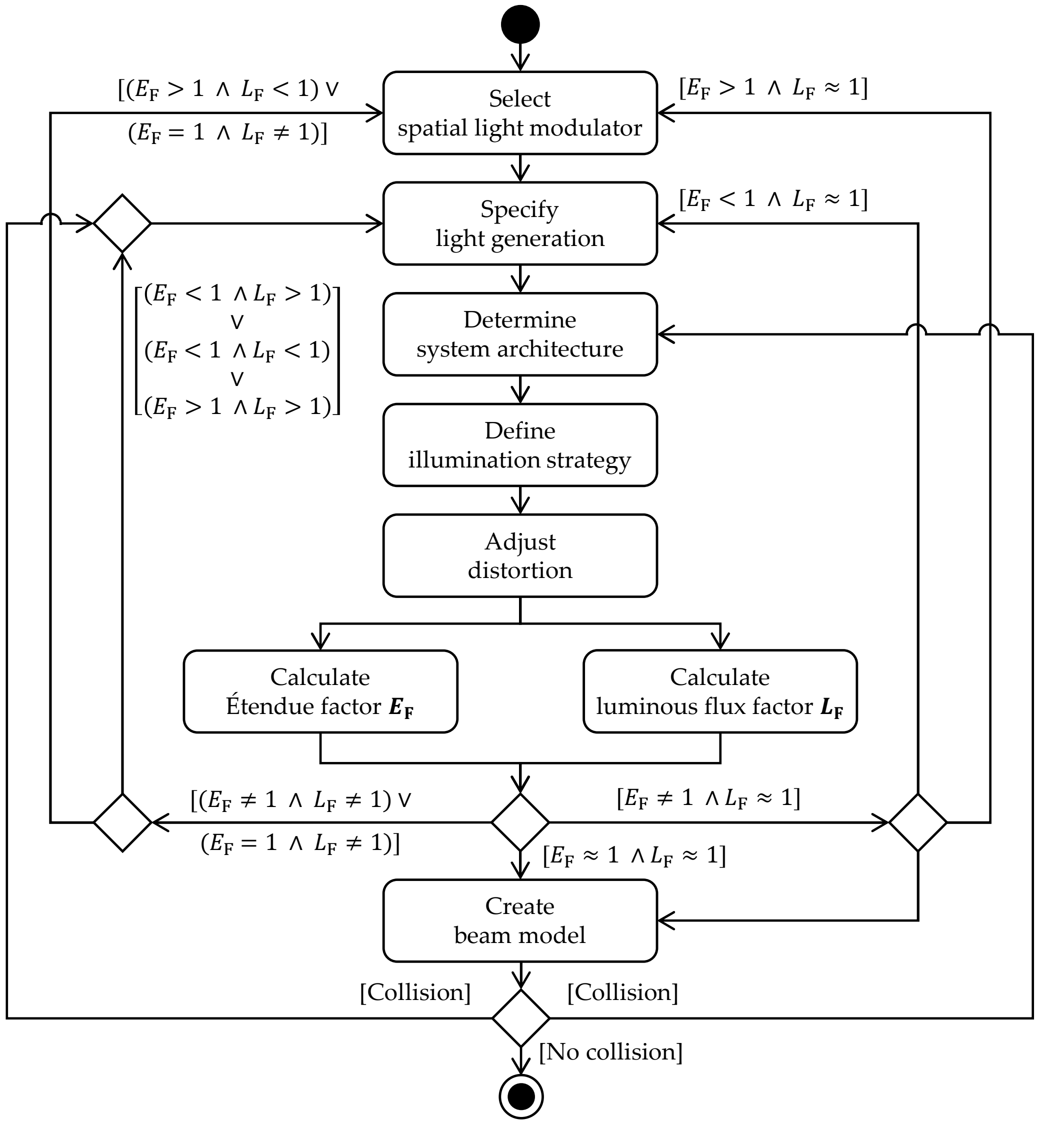

Figure 7. Method for the preliminary design of high-resolution lighting systems according to [16].

- **Determine system architecture:** When determining the architecture of the high-resolution lighting system, not only the type and number of optical elements to be used for beam shaping and deflection are specified, but also the spatial arrangement of these elements required for implementation. Depending on the defined technologies for light modulation and generation as well as on the elicited requirements, different system architectures are feasible. Using a light modulator, the optical system of a high-resolution lighting system can be divided into a subsystem to illuminate the light modulator and a subsystem to project it into the application area. Both subsystems are functionally as well as spatially interdependent. Functional dependence arises from the strategy to illuminate the active area of the modulator (cf. paragraph Define illumination strategy) and the lighting of the projection area (cf. paragraph Adjust distortion). The spatial dependence derives from the chosen technology for light modulation, which at the same time affects the Étendue of the system. For example, when using a DMD to implement a non-telecentric system architecture, higher angles are required to illuminate the light modulator in order to achieve sufficient separation of the incident light from the illumination system and the light reflected into the projection system than with a telecentric system architecture. As the illumination angle increases, the seemingly illuminated area of the light modulator is reduced, thus reducing the Étendue of the DMD.

- **Define illumination strategy:** Strategies to illuminate the active area of the modulator can be differentiated primarily into imaging and non-imaging and secondarily into homogeneous and inhomogeneous [31,57]. According to photometric regulations for headlamps, which are specified in various ECE regulations, an inhomogeneous distribution of illuminance within the traffic area is required [58–60]. Therefore, it seems to be obvious to use an inhomogeneous strategy to illuminate the active area of the modulator. However, an inhomogeneous illuminance distribution of the active area of the modulator, regardless of whether it is generated imaging or non-imaging, can lead to a damage of individual micromirrors or of the entire light modulator due to the irregular heat input in case of insufficient cooling. Using imaging illumination strategies, a precise illumination of the active area of the modulator is possible given appropriate manufacturing and assembly tolerances of the optical and mechanical components. Luminous flux losses, which occur when using non-imaging illumination strategies due to illumination overfill of the active area of the modulator [61,62], are therefore reduced. However, as a result of the functional dependence between the illumination and projection optics, the overall efficiency of high-resolution lighting systems for vehicle front illumination can be increased using a distortion of the projection system adjusted to the inhomogeneous illumination strategy [63].
- **Adjust distortion:** In order to meet the photometric requirements, a distortion of the projection optics is determined that is adjusted to the illumination strategy, taking into account the subsystem that illuminates the active area of the modulator. Usually an aberration in optical systems, distortion does not lead to blur but to a distortion of the projected image and thus to a positionally variant image scale [64,65]. For example, anamorphic distortion can be used to change the image scale in horizontal and/or vertical direction. Thus, the geometry of the illuminated area can be decoupled from the aspect ratio of the light modulator [12,63]. In addition to a variable pixel size, a pincushion distortion also enables a redistribution of the illuminance, which benefits the application as a headlamp [66,67].
- **Calculate Étendue factor:** To evaluate the Étendue conservation and thus the efficiency of the high-resolution lighting system, the so-called Étendue factor (E_F) is defined. Defined as the ratio of the Étendue of the light source to the Étendue of the light modulator [68], efficient preliminary designs are indicated by an Étendue factor of approximately one $(E_F \approx 1)$. Inefficient preliminary designs are characterized by an Étendue factor of significantly greater $(E_F > 1)$ or less $(E_F < 1)$ than one. However, since both an efficient and inefficient preliminary design cannot be considered equivalent to the fulfillment or non-fulfillment of photometric requirements, a so-called luminous flux factor (L_F) is also defined.
- **Calculate luminous flux factor:** The luminous flux factor is used to ensure the preliminary design with regard to the feasibility of photometric requirements and is described by the ratio of actual to target luminous flux on the active area of the modulator. The target luminous flux is determined using the required luminous flux in the light distribution based on assumptions about the efficiency of the subsystem for projection as well as the illumination overfill of the active area of the modulator. The actual luminous flux is determined using the Étendue and thus the usable portion of the luminous flux from the light source to illuminate the active area of the modulator, as well as assumptions about the efficiency of the subsystem used for illumination. For preliminary designs indicated by a luminous flux factor of approximately and greater than one $(L_F \approx 1, L_F > 1)$, the photometric requirements can be realized. Preliminary designs indicated by a luminous flux factor of significantly less than one $(L_F < 1)$, the photometric requirements cannot be met.
- **Case analysis:** Within the scope of the case analysis shown in Figure 7, the developed preliminary designs are evaluated with regard to the conservation of Étendue and the fulfillment of photometric requirements. The occurring cases can be divided into the following three categories:

  - Category 1 is associated with cases $[(E_F \neq 1 \wedge L_F \neq 1) \vee (E_F = 1 \wedge L_F \neq 1)$, where the photometric requirements cannot be realized due to a too low luminous flux factor;
  - For preliminary designs of category 2 $[(E_F \neq 1 \wedge L_F \approx 1]$, the photometric requirements are met, but due to an Étendue factor considerably differing from one, these designs are characterized by inefficiency. Consequently, either the light source or the light modulator is oversized;
  - If the photometric requirements and simultaneously the Étendue conservation are fulfilled, then the preliminary designs are of category 3 $[(E_F \approx 1 \wedge L_F \approx 1]$, allowing to proceed directly to the last design step of the method.

  For category 1 and 2 designs, loops are provided within the method to return to specific design steps for targeted optimization. An explanation of when to return to which design step can be found in [17].

- **Create beam model:** In the final step, a beam model is created for the preliminary design of the high-resolution lighting system, which serves as the basis for the domain-specific detailed design of the optical system. The beam path of the high-resolution lighting system is designed from the light source on the object side to the projection area on the image side. Furthermore, the beam model can be used to identify system configurations in which, for example, individual optical elements or the subsystems for illumination and for projection collide. Occurring collisions can be resolved via loops within the method to the steps "Determine system architecture" and "Specify light generation", which is explained in more detail in [17].

As a result of the method, various preliminary designs of the high-resolution lighting system are thus available in terms of beam models. For each beam model, in addition to the modulation technology to be used and the number and size of the light modulator as well as the light source(s), the type and number of beam shaping and deflecting optical elements as well as their spatial arrangement in the system are known. Furthermore, the focal length and the image scale are known.

The beam model describes a possible implementation of the optical system, taking into account the concept-defining requirements. This can be used as a basis for creating a computational model of the optomechatronic overall system in order to carry out detailed analyses of the optical system or also of cross-domain interactions. The evaluation and subsequent selection of the concretized solution variants is based on the requirements. Methods widely used in design theory, such as the optimized cost analysis from VDI 2225 [69], can also be applied in the context of optomechatronic systems. At the end of the system design process, a solution concept has been elaborated that meets the requirements.

3.2. Extension of the Process Phase for Domain-Specific Design by the Method for the Detailed Design of High-Resolution Lighting Systems

The system design phase is followed by the further elaboration of the previously selected solution concept in the domain-specific design (Figure 8). According to VDI Guideline 2206, this task is separated into the domains of mechanics, electronics and software [10]. Within the domains, adapted methods and computer tools are used, which makes the separation into domains necessary. For optomechatronic systems, this approach is also applicable by adding optics as another domain. However, at specific points in the domain-specific design, we recommend that data and models be shared between domains. In particular, interactions between the domains mechanics and optics have to be considered, since for example mechanical tolerances have a significant influence on the optical image quality. Furthermore, mechanical components in or near the optical path can be possible sources of stray light, so these components should be considered in a detailed stray light analysis.

The process to develop optomechatronic systems allows the developer to decide how the detailed design will be carried out and how the aforementioned interactions between the domains mechanics and optics can be analyzed and considered. In the context of the tangible adaptation of the process to high-resolution lighting systems, the work steps shown in Figure 8 within the optics domain are further detailed by Ley's method for the sequential and non-sequential detailed design [17].

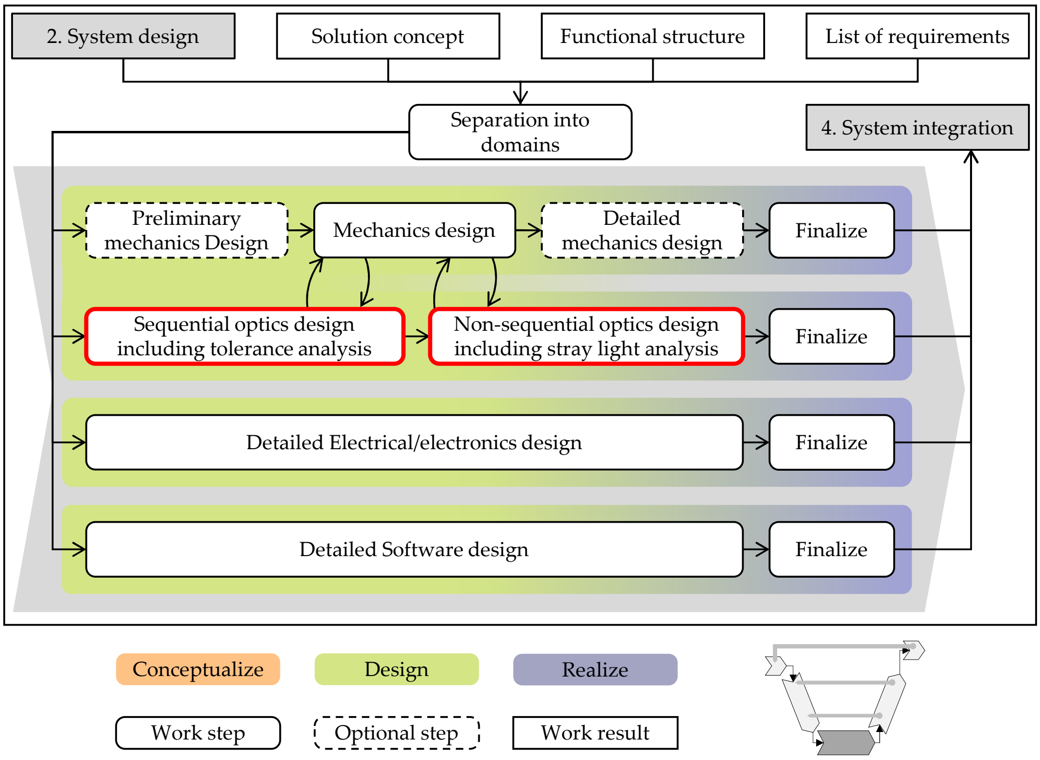

Figure 8. Process phase for the domain-specific design of optomechatronic systems according to [9] extended by the method for the sequential and non-sequential detailed design of high-resolution lighting systems according to [17].

So-called ray tracing programs such as Zemax OpticStudio®, CODE V or 3DOptix are used for the detailed design of optical systems. Starting from the object side, rays are traced through the optical system to the image side. Basically, the type of ray tracing can be divided into sequential and non-sequential. The detailed design of imaging optical systems, such as the subsystem for projection in high-resolution lighting systems, is primarily performed using sequential ray tracing. This kind of ray tracing allows not only a fast optimization but also the analysis and definition of required tolerances with regard to image quality. Detailed designs of illumination optics, on the other hand, such as the subsystem to illuminate the light modulator, are primarily developed using non-sequential ray tracing. This is because, among other things, scattered and reflected radiation as well as absorption losses can be taken into account in the detailed design and thus predictions can be made about the efficiency.

However, with regard to the overall efficiency of high-resolution lighting systems, besides the efficiency of the subsystem to illuminate the light modulator, the efficiency of the subsystem for projection into the traffic area is also relevant. In addition, the image quality of imaging optical systems is also affected by scattered and reflected radiation, so non-sequential ray tracing must be considered for both the detailed design of illumination optics and imaging optics. Conversely, fast optimization in context of sequential ray tracing is also suitable for detailed designs of illumination optics [70]. Consequently, with respect to the conflict of objectives between optical efficiency and image quality mentioned in Section 1.2, both ray tracing techniques have to be considered in the detailed design of high-resolution lighting systems.

In the following, the method for the combined sequential (SC) and non-sequential (NSC) detailed design of high-resolution lighting systems is explained step by step. The design steps shown in Figure 9 are performed regardless of the ray tracing program used, although their order may vary. The order of design steps shown in Figure 9 is based on the use of Zemax OpticStudio® for ray tracing.

3.2.1. Design Steps for the Sequential Detailed Design (SC-Design)

Based on the beam model, which was created using the method for the preliminary design of high-resolution lighting systems in the framework of the system design for optomechatronic systems, the sequential detailed design of the high-resolution lighting system is carried out first. In the first step, the emission characteristics and area of the light source are defined.

- **Define emission characteristics and area:** Reduced to individual emission points—so-called fields, from which the spatial propagation of the rays emitted by the light source occurs—the size of the emission area is defined. For the description of the emission area, the arrangement of several fields is beneficial in order to achieve a high accuracy in ray shaping of the subsequent functional surfaces. Rays, which shall be considered by the following functional surface (e.g., mirror or surface of a lens) for shaping or deflection, can be defined by the emission angle of the fields as well as by the entrance pupil or numerical aperture of the functional surface. In addition, for both monochromatic and polychromatic light sources, the wavelength(s) must be specified.
- **Set functional surfaces and parameters:** Based on the parameters obtained from the beam model, such as the type and number of optical elements for beam shaping and deflection, as well as the focal length and the image scale, the functional surfaces, parameters and boundary conditions of the optical system can be defined. Refractive optical elements such as lenses or prisms are defined by the combination of two respectively three functional surfaces in Zemax OpticStudio®. The thickness of the optical element and the material are determined by the first functional surface. Reflective optical elements such as reflectors or plane mirrors are defined by a single functional surface, specifying reflective material properties. Once all functional surfaces for the sequential detailed design have been defined, functional surface parameters such as radii, materials or distances, which may or may not be changed during the optimization of the detailed design, are defined. To obtain a first approximation, it is advantageous to limit the number of variable parameters in the early phase of the detailed design. With increasing maturity of the sequential detailed design, the number of variable parameters of the functional surfaces can be increased in context of optimization loops. The parameter values should be limited in consideration of manufacturability and mountability of the optical elements. Finally, boundary conditions are defined, which arise in particular from the requirements initially elicited.
- **Create Merit Function:** As an expression of design objectives to be met and achieved, a so-called merit function must first be defined for the optimization of the sequential detailed design. By restricting variable parameters due to minimum and/or maximum values, design goals to be met are defined. This may lead to several valid design solutions during optimization. An example is the length of the optical system, which should not exceed a certain maximum value due to requirements. Thus, with respect to the maximum length of the optical system, several designs can be developed to meet this requirement. If the variable parameters are defined by a single value, these are design goals to be achieved, with only one valid design solution. As an example of design objectives to be achieved, a defined field of view, which has to be illuminated according to the requirements, can be mentioned at this point. Design objectives to be met and achieved, which are derived from the requirements for the sequential detailed design, are thus coupled to the freedoms in the merit function, which in turn correlate with the number of variable parameters.

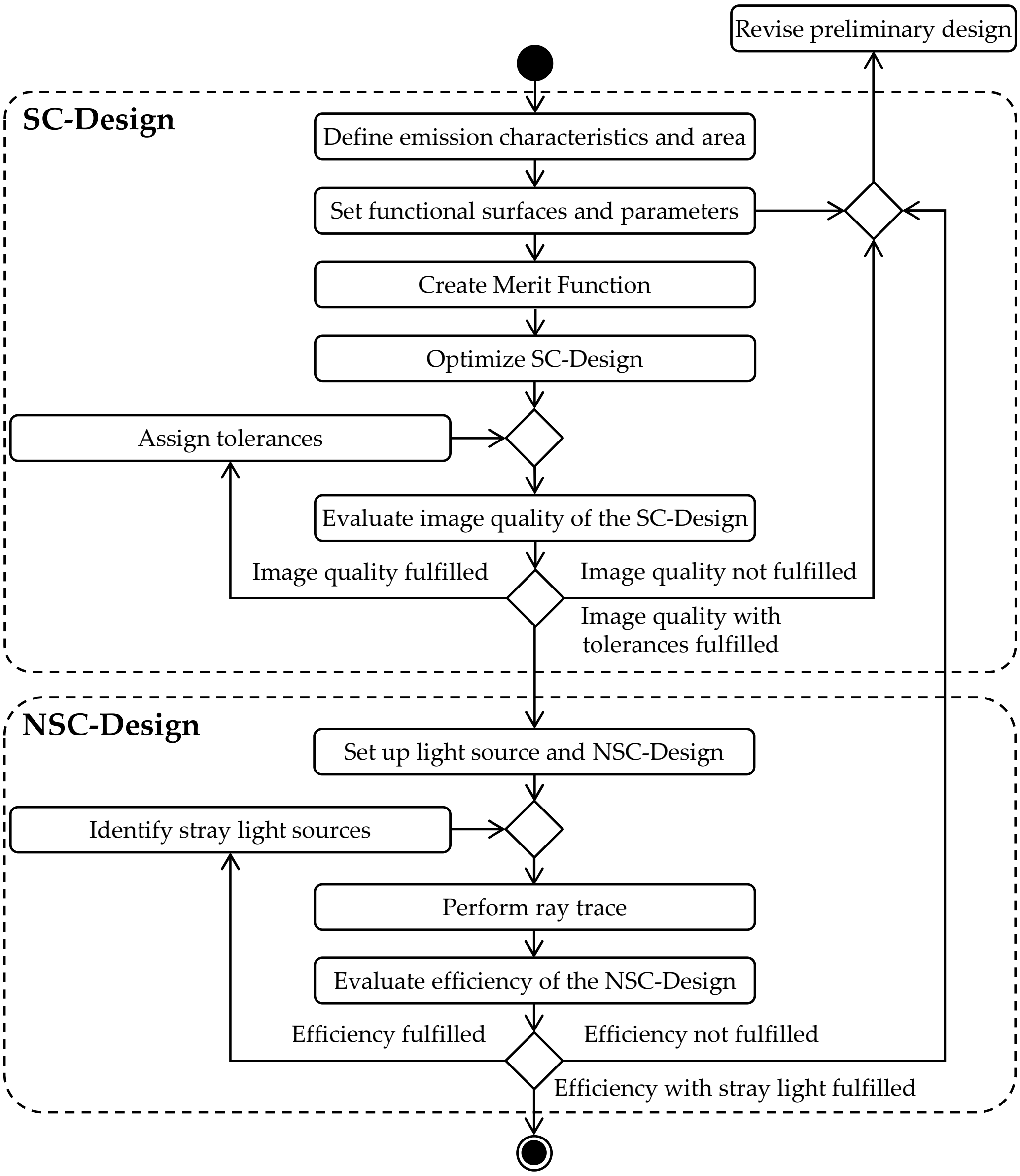

Figure 9. Method for the sequential and non-sequential detailed design of high-resolution lighting systems according to [17].

- **Optimize SC-Design:** Within the optimization step, the optimization type, the optimization algorithm and the number of optimization cycles have to be defined. The type of optimization can be divided into so-called "local" and "global" optimization [53]. In the early phase of the design process, "global" optimization is particularly suitable for an initial estimation. As the sequential detailed design matures, effective improvements can be achieved quickly using "local" optimizations. The algorithm for the optimization of the detailed design has to be chosen depending on the function of the optical system (imaging or illuminating) as well as on the selected optimization type. Especially developed for detailed designs of optical systems, algorithms that operate according to the "Damped Least Squares" method are generally suitable [71]. The number of optimization cycles to be performed has to be defined depending on the design progress. Similar to the definition of variable parameters, a limited number of cycles is recommended in the early phase of the design process, which can be increased with the growing maturity of the sequential detailed design.
- **Evaluate image quality of the SC-Design:** On the basis of the design of an imaging optical system, the image quality of the sequential detailed design must be evaluated

after the optimization step. For the design of illumination optics, this step can be skipped. Different criteria such as modulation transfer function (MTF), point spread function (PSF), encircled energy (EE), RMS spot radius, wavefront, and aberrations are used to evaluate the image quality [51,52,72,73]. The choice or suitability of an evaluation criterion is significantly influenced by the subsequent field of application of the optical system. For example, detailed designs of lenses used in the field of photography are evaluated using the MTF, and optical designs of LiDAR systems are often evaluated using the EE criterion [74–77]. In case the required image quality of the sequential detailed design is not met, return to step "Set functional surfaces and parameters" (cf. Figure 9). If the requirements for the image quality are not met despite repeated runs through this loop, the preliminary design of the high-resolution lighting system must be revised (cf. Figure 9).

- **Assign tolerances:** Since deviations due to manufacturing and alignment affect the image quality of the sequential detailed design, tolerances must be assigned to the individual functional surfaces and the image quality must be re-evaluated. Deviations caused by the manufacturing process (ultra-precision turning, CNC machining, etc.) must be taken into account by tolerancing the detailed design with regard to the position and surface of the functional surfaces. The influence of alignment-related deviations of individual optical elements in the manufactured optical system can be taken into account by decentering and tilting the functional surfaces in the sequential detailed design. If the requirements for the image quality of the sequential detailed design are met, while taking the assigned tolerances into account, one can continue with the assembly of the non-sequential detailed design. Otherwise, return to the step "Set functional surfaces and parameters".

3.2.2. Steps for the Non-Sequential Detailed Design (NSC-Design)

For the analysis of scattered and reflected light, as well as absorption losses in the optical system, a non-sequential detailed design is used, allowing conclusions about the optical efficiency of the system (cf. Section 3.2). Therefore, the simplified emission characteristics and area of the light source(s) of the sequential detailed design have to be replaced by a more realistic light source.

- **Set up light source and NSC-Design:** The simplified emission characteristics and area of the light source of the sequential detailed design is replaced by a so-called ray file, from which the measured spatially resolved radiance of the light source from different angular positions is described [78]. Alternatively, a modeling of the light source with appropriate angular and spatial resolution of the luminous intensity can be carried out according to the data sheet. Subsequently, the number of rays required for tracing has to be determined, which should be high in terms of an accurate conclusion about the efficiency. Furthermore, the luminous flux of the source, as well as the emitted wavelength(s), have to be specified. For precise statements about the efficiency of the high-resolution lighting system, not only the light source but also the light modulator must be modeled as accurately as possible, and material, coating and scattering definitions must be assigned to the optical volume elements (lenses, prisms, etc.).
- **Perform ray trace:** Taking into account the angular and spatially resolved luminous intensity of the light source, a defined number of rays are traced through the optical system. The single rays are affected by different optical effects like refraction, diffraction, (total) reflection, scattering, splitting or absorption or a combination of these effects, which depend on the assigned material, coating and scattering definitions as well as on the individual optical elements.
- **Evaluate efficiency of the NSC-Design:** The evaluation of the efficiency of the non-sequential detailed design is carried out on the basis of the performed ray trace. In addition to determining the overall efficiency, it is also recommended to determine the efficiencies of the individual optical elements in order to be able to conduct

targeted measures to increase efficiency during optimization loops. If the overall efficiency and/or the photometric requirements (e.g., lighting functions to be realized or photometric quantities) of the high-resolution lighting system are not met, it is advisable to return to the design step "Functional surfaces, parameters and boundary conditions". If no improvement is achieved despite running through this loop several times, a second loop must be used to return to the phase of preliminary design (cf. Figure 9).

- **Identify stray light sources:** In order to identify unwanted scattered and reflected light, which may have negative effects on the optical properties of the non-sequential detailed design, a stray light analysis must be performed. Both optical and mechanical components that lead to an unwanted reduction in contrast and/or image quality are analyzed. An effective approach to identify stray light at surfaces of the optical and optomechanical design is to examine the optical system from the object and image sides. For this purpose, based on the previously performed ray trace, selected rays are analyzed with respect to their interaction with surfaces and subsequently measures for the reduction of stray light are implemented. According to Breault [79], the application of anti-reflective coatings, the positioning of aperture stops at suitable points in the optical path or the constructive redesign of individual components are particularly effective measures for the reduction of stray light. The exchange of information between the optics and mechanics domain is therefore essential with regard to the respective domain-specific design (cf. Figure 8). The effectiveness of the implemented measures shall be verified by means of a repeated ray trace with subsequent evaluation of the efficiency. If the requirements for the efficiency of the non-sequential detailed design are met, the method ends.

As a result of the method for the sequential and non-sequential detailed design, a design of the optical system is provided which meets the requirements with regard to the conflict of objectives between optical efficiency and image quality (see Section 1.2). Influences on the image quality due to deviations of the mechanical and optical components caused by manufacturing and alignment can be assessed for this detailed design. Furthermore, it is known on which surfaces of the optical and mechanical components scattered and reflected light occurs and by which measures these can be prevented or reduced. In addition to the overall efficiency for evaluating the optical efficiency, the efficiencies of the individual optical elements are also known.

Finally, manufacturing documents such as single part drawings and parts lists are generated for the detailed design of the optical system but also for the components of the other domains. This provides all the necessary information and data for the subsequent phase of system integration and property validation.

3.3. System Integration and Property Validation Process Phase

In the phase of system integration, the components are successively combined to subsystems which are then assembled to an overall system. After each integration step, previously specified tests are performed to ensure proper integration of the system functions. With regard to optomechatronic systems, the interactions with humans must also be taken into account when validating properties. These are often not completely incorporated in models, so that a final validation step with the complete system in the field is recommended.

For high-resolution lighting systems, the process phase for system integration and property validation shown in Figure 10 can be applied unchanged. The contents of the system integration and property assurance phase are summarized below. As shown in Figure 10, the necessary information and data for manufacturing or procuring the system components are available after the domain-specific design.

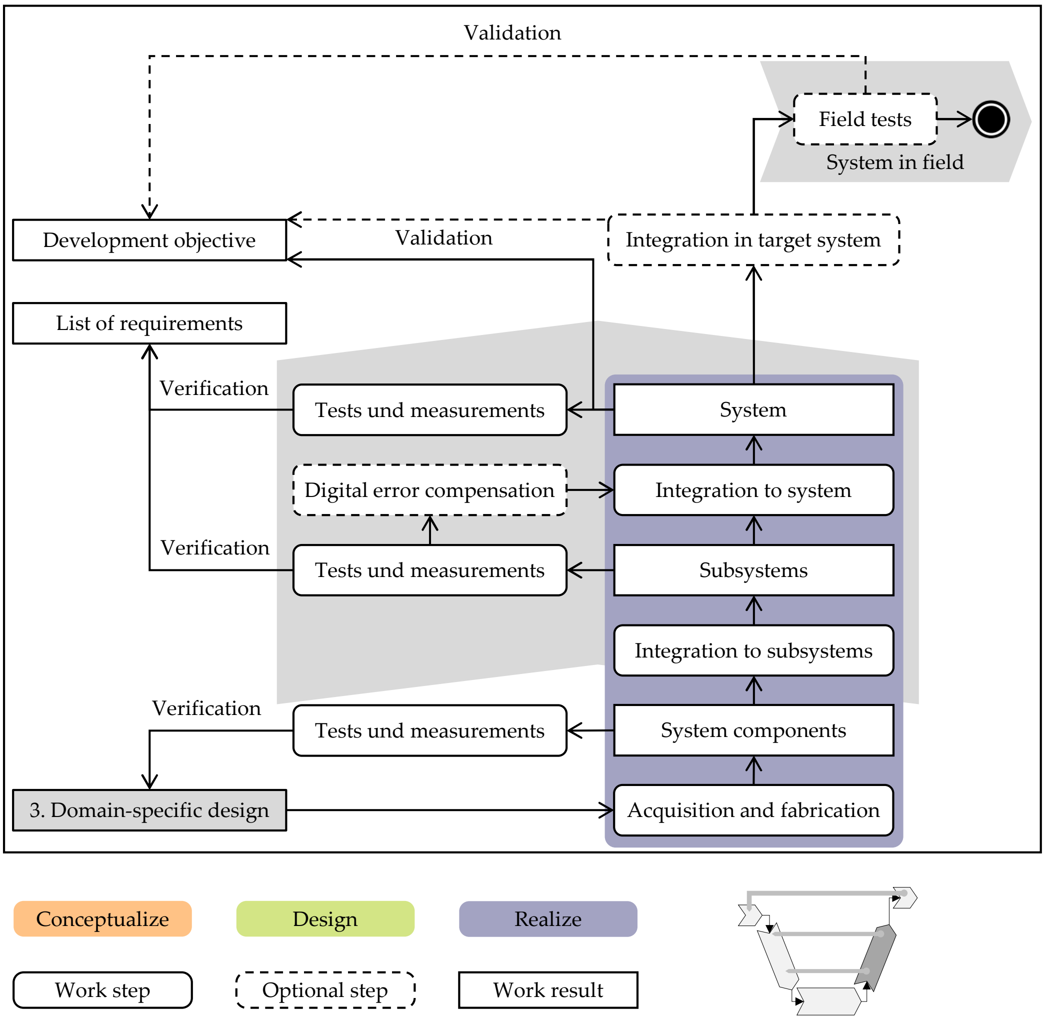

Figure 10. Process phase for system integration and assurance of properties according to [9].

Prior to the actual integration, the system elements are subjected to tests to ensure the specified properties. After each integration step, further measurements and tests are performed to ensure the correct integration of the functions and to verify them with respect to the specified requirements. For optomechatronic systems and especially for high-resolution lighting systems, digital error compensation methods can be used to compensate for deviations. After integration into the overall system, validation is performed against the development goal.

4. Application Example

The methods introduced in this contribution for the development of optomechatronic systems as well as for the preliminary and detailed design of high-resolution lighting systems are demonstrated by practical application examples from research projects in the works of Knöchelmann and Ley [9,17].

On the basis of these application examples, the concretizations of the process phases system design and domain-specific design of the adapted V-Model for high-resolution lighting systems are discussed at specific points.

In the following, the selected cross-domain solution concept is shown in Section 4.1 and a detailed simulation model of these application examples is described in Section 4.2, justifying the specific steps of the methods.

4.1. System Design: Cross-Domain Solution Concept of a High-Resolution Lighting System

The solution concept shown in Figure 11 is the outcome of the system design of a research project on high-resolution headlamps. The principle solution shown was derived from a functional structure based on analyses with a prototype [66,80]. A key decision was the application of a light modulator based on subtractive image generation ("DMD" in Figure 11), which is characterized by high resolution [27]. Controlling the light source essentially involves having control over the output luminous flux. Operating the light modulator requires a complex controller that switches the individual micromirrors of the DMD according to the required light distribution.

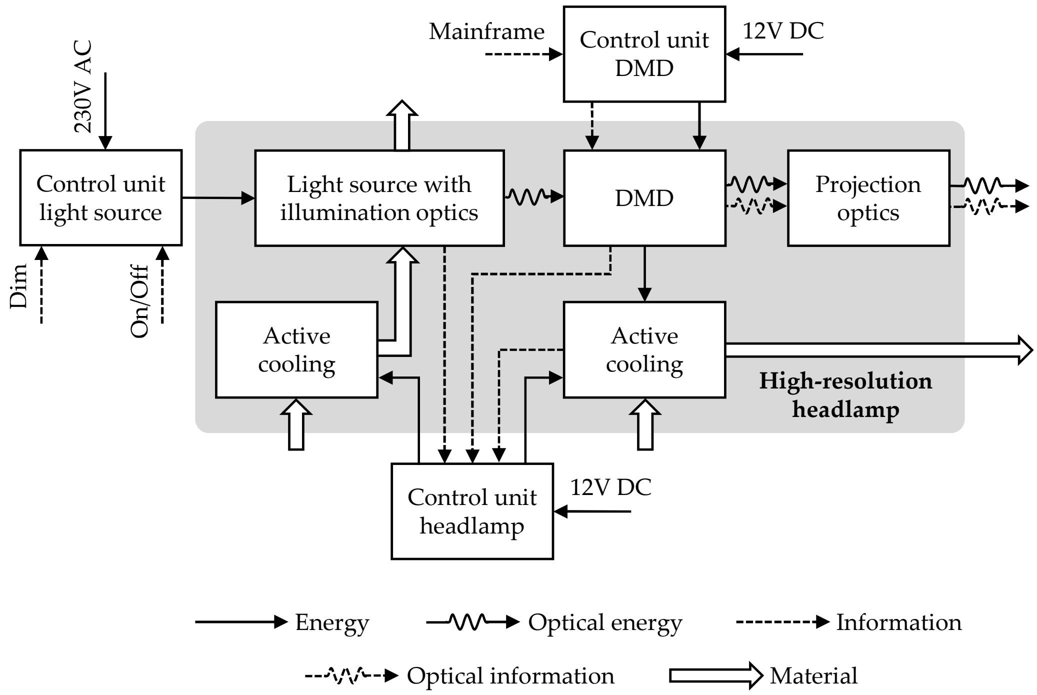

Figure 11. Cross-domain solution concept of a high-resolution lighting system according to [9].

The majority of the system's heat loss is expected in the area of the light source and at the light modulator with this concept. Due to the functionally required gaps between the individual micromirrors, about one third of the incident light is absorbed and correspondingly converted into heat. In order to keep the light source and light modulator within the operating temperature range, active cooling is provided. From the selection of the light modulator the required illumination optics including light source follows, for which standard components are selected. As a projection optics, a prototype of a special distorting optics is provided, which was developed and patented within the research project [66,67].

Based on the concept shown, a prototype of a complete high-resolution headlamp is build to meet the lighting requirements of the research project [9]. However, the conflict of objectives between high optical efficiency and image quality is not sufficiently considered, which is, however, necessary with regard to the suitability of the system for series production. By concretizing the process model, a detailed design with tailored optical elements is made possible, so that a comprehensive trade-off between optical efficiency and imaging quality can be made.

4.2. Domain-Specific Design: Non-Sequential Detailed Design of a High-Resolution Lighting System

In order to achieve a comprehensive trade-off between optical efficiency and image quality, a detailed design of the high-resolution lighting system was carried out on the basis of the concept presented in Section 1.2. First, the superior decisions that led to the detailed design shown in Figure 12 are explained, followed by a discussion of potentials to increase optical efficiency.

To illuminate the active area of the modulator, the Osram Oslon® Boost HL LED has been selected as a light source. Taking into account the Étendue of the DLP7000, used as light modulator, a 2 × 4 LED array can be implemented for light generation. In order to realize an Étendue-preserving system, a telecentric system architecture is determined for the high-resolution lighting system, implemented using a TIR prism to ensure sufficient separation of the illumination and projection paths [30,81].

A homogeneous illumination of the active area of the modulator, with the objective to reduce luminous flux losses due to an illumination overfill, and the application of identical LEDs for the LED array allows the use of identical LED optics. Designed as a collimator to achieve efficient use of the light emitted by the LEDs, the LED optics are combined to create a lens array. The homogeneous illumination of the active area of the modulator is achieved by means of the subsequent converging and free-form lenses. Depending on the position of the micromirrors, the incident light on the active area of the modulator is projected into the application area via a three-lens projection system. The image quality of the projection system has been analyzed in the work of Ley [17].

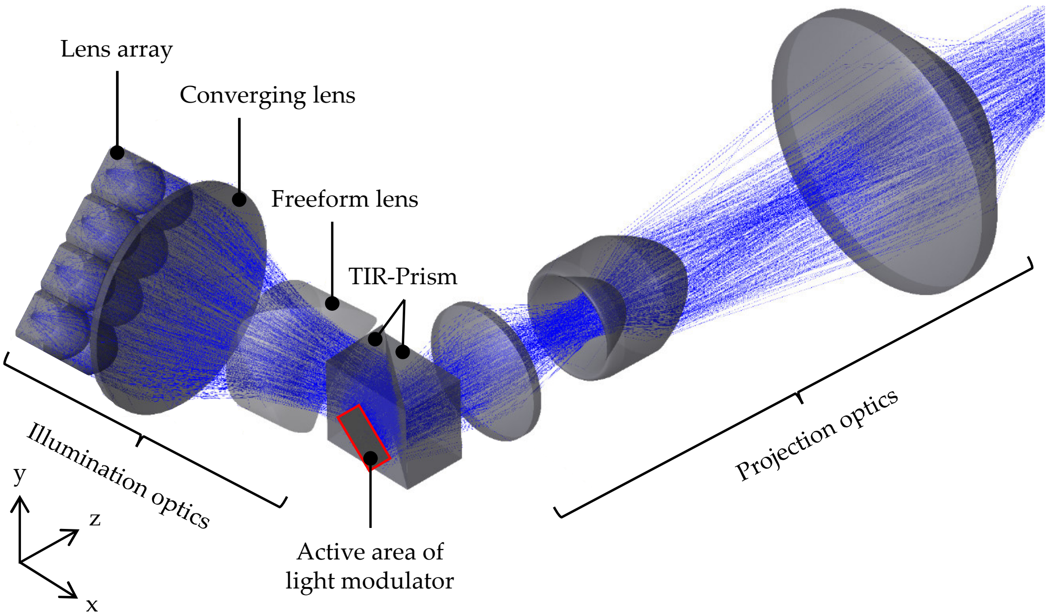

Figure 12. Non-sequential detailed design of a high-resolution lighting system according to [17].

Based on an analysis of the detailed optical design, Ley identified in [17] various areas in the optical path where different measures can be performed to increase the optical efficiency. In the following, an excerpt of possible solutions to increase the optical efficiency is presented using the example of the TIR prism, taking into account interdependencies between the domains mechanics and optics (cf. Figure 8).

Alignment deviations between the TIR prism and the active area of the modulator, which for example lead to rotation, tilting or displacement of the components relative to one another, have a significant influence on the illumination overfill of the active area of the modulator and thus on the efficiency of the system. To minimize the influence of alignment deviations, it is therefore recommended to use a single optomechanical mount to embed both components. The mounting shall be designed in such a manner that the tolerances of position between the two components are maintained during assembly and operation, that twisting, tilting and/or displacement between the two components is prevented, and that centering is achieved at the same time.

One optical approach to increase the system efficiency is to integrate the optical function of the free-form lens into one of the two prism halves of the TIR prism [82].

Although not described in [82] by Penn, this approach is suitable to increase the system efficiency, since a reduction in the number of optical elements in the system also reduces the losses due to scattered and reflected light at the individual optical elements.

The example of the non-sequential detailed design of the high-resolution lighting system allows us to illustrate how, by integrating the method for the sequential and non-sequential detailed design into the process to develop optomechatronic systems, targeted measures can be realized to address the conflict of objectives between high optical efficiency and image quality during the development of these systems.

5. Summary and Conclusions

The increasing complexity of high-resolution lighting systems in combination with the demand for high optical efficiency and image quality lead to the fact that established methods like the VDI guideline 2206 reach their limits. Therefore, in this contribution we introduce a V-Model to develop optomechatronic systems, in which both the concept-defining properties of the domain optics and the effect of these systems on humans are taken into account. Concretized in the phases of system design and domain-specific design by methods for the preliminary and detailed design of high-resolution lighting systems, we show how the conflict of objectives between high optical efficiency and image quality can be addressed.

For this purpose, the concretization of principle solution variants is extended by specific design steps for high-resolution lighting systems within the phase of the system design. As a result, various preliminary designs of the high-resolution lighting system are available by means of beam models, which are used as the basis to create computational models of the overall optomechatronic system. The subsequent optional analysis of cross-domain interactions is used to derive solution variants of the overall system. The further elaboration of the selected solution concept in the phase of the domain-specific design is made concrete for the domain optics by the method for the sequential and non-sequential detailed design of high-resolution lighting systems. Finally, a detailed design of the optical system is available for the high-resolution lighting system, in which both influences on the image quality and optical efficiency can be quantified as well as measures to increase them are known (cf. Figure 9: Design step "Evaluate image quality of the SC-Design" resp. "Evaluate efficiency of the NSC-Design").

Once the manufacturing documents have been prepared and all components in the optical, mechanical, electronic and software domains have been procured, the next stage is system integration and property validation. In this process phase, the components of the system are first successively assembled into subsystems, which are then used to set up the overall system. The final property validation of optomechatronic systems is carried out taking into account interaction with humans.

Finally, the integrated process model is illustrated by practical application examples from research projects in the works of Knöchelmann and Ley [9,17]. Using the example of the cross-domain solution concept from the work of Knöchelmann [9], restrictions are discussed with respect to the conflict of objectives between optical efficiency and image quality using standard components to realize the optical system. In order to demonstrate opportunities to address this conflict of objectives by using tailored optical elements, the non-sequential detailed design of a high-resolution lighting system from the work of Ley is analyzed [17].

In this contribution, the process to develop optomechatronic systems of [9] by Knöchelmann is presented, which can be extended by specific adaptations of the process phases. Which process phase and which steps within the process phase have to be adapted is significantly influenced by the main function of the optomechatronic system to be fulfilled (cf. Figure 1). For example, the system in [5] by Kanngiesser, Rahlves, and Roth, referred to in Section 1.1, requires an adapted approach for the preliminary design of the optical system. With the objective of increasing the penetration depth for non-invasive imaging in the field of medical diagnostics using a light modulator, the main function "Measure" is realized. Besides light generation and modulation, optical elements for beam splitting and polarization as well as a spectrograph are used for this purpose. The selection of a suitable spectrograph as well as elements for beam splitting (beam splitting cubes, beam splitting plates, etc.) and polarization (dichroic polarizers, reflective polarizers, etc.) must be taken into account as part of the preliminary design.

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