An Approach for Cross-Domain Optimization for Automated Adaptation Design of Mechatronic Systems

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Abstract

The product development of mechatronic systems remains complicated as interdisciplinary system interrelations and divergent requirements from the involved engineering domains must be taken into account. Thus, the inherent complexity and interdependencies of mechatronic systems usually require an iterative procedure to generate an optimized product even for small design adaptations. Therefore, the proposed approach aims to automate subprocesses in the adaptation design of mechatronic systems from the problem identification to the optimized product. It involves a cross-domain optimization by utilizing the knowledge from previous product development cycles and optimization histories. The approach is demonstrated using an electronic window regulator as an example.

Keywords

Adaptation Design, Mechatronic Systems, Knowledge-Based Engineering, Optimization, Systems Engineering

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1. Motivation

Mechatronic systems are ubiquitous in many fields. Especially mechatronic adjustment systems form the basis for the automation of various tasks, including electronically controlled movements. Due to the similarity of adjustment systems, existing products are often utilized as basis for their development. Thus, products can be easily adapted with respect to slightly changed requirements, while partially reusing existing documents and models of the predecessor. This adaptation design is characterized by the fact that the solution principle remains the same [1]. Nevertheless, the product development remains a challenging endeavour due to the consideration of interdisciplinary system relations and the presence of divergent requirements from the involved engineering domains. This is particularly crucial because relations may remain unrecognized and have a far-reaching effect on the adaptation design process [2] since even minor technical changes can affect other segments of the system [3]. Thus, a simultaneous consideration of mechanic, electronic and software design is necessary, which makes the adaptation design process of mechatronic systems complex and time-consuming. In order to overcome these hurdles, this paper proposes a new approach for automated adaptation design. It is organized as follows: Chapter 2 discusses the state of the art. Chapter 3 elucidates the necessity for research, while Chapter 4 delineates the approach. Finally, a case study is presented in Chapter 5 and a conclusion is given in Chapter 6.

2. State of the art

In light of the above, the fundamentals for mechatronic system development, described in the VDI 2206, are given, followed by a current state of research in this field. The VDI 2206, entitled "Development of mechatronic and cyber-physical systems", is a guideline for the development of mechatronic systems with the objective of establishing a standardized understanding. It is designed to provide comprehensive methodological support for developers, while not specifying the methods or tools to be employed. One component of the VDI 2206 is the development process of mechatronic systems. The V-model represents the complete cycle from requirements elicitation up to handover to realization or production. In the left branch, a decomposition of the complex task into functions, logical and physical structure including partitioned subsystems and system elements takes place. The system elements are then implemented in the individual domains. Finally, the implemented system elements are reintegrated into an overall system in the right-hand branch, with the system properties being continuously verified and validated. [4]

The field of mechatronics has attracted the attention of researchers and scientists in particular due to the combination of the three domains of mechanics, electrical engineering and informatics. This led to numerous research approaches, albeit with a large variance in the research focus, ranging from requirements and defined goals [5] to optimization methods [6]. The complex, cross-domain interrelationships pose a major challenge and are subject of many publications. For example, Torry Smith et al. [7] investigate the interdependencies between the domains, striving for their intensive consideration in the development process. In this sense, Ahmad et al. [8] investigate the traceability of changes from the requirements to the design draft, concluding that the application of a cross-domain representation will be beneficial. This holistic representation of the system is intended to unify the domains and generate a common understanding. Qamar et al. [9], for example, aims to identify the dependencies between the domains by using a multidisciplinary model, such as a system model using SysML. Tian et al. [10], on the other hand, use multidisciplinary simulations and their results as the basis for subsequent multidisciplinary design optimization. Due to constant progression and the drive to improve products and processes, system optimization is playing an increasingly important role. Multidisciplinary optimizations are of particular interest in the field of mechatronics. The numerous variations of mechatronic systems and their different optimization problems lead to a diversity, especially in the implementation of the optimization process. The optimization topic is examined, e.g., by EL-Kribi et al. [11], who show an approach for mechatronic systems in which a global optimization problem for a motor was derived and subsequently solved as part of a multi-objective optimization using the NSGA II algorithm. For example, Da Silva et al. [12] present an approach for the optimal design of mechatronic systems, where based on a generated model of the system, an optimization is carried out using the NSGA II optimization algorithm.

One field that is increasingly being used in connection with mechatronic systems is Knowledge-based Engineering (KBE), which deals with methods and technologies for capturing and reusing knowledge, aiming to reduce costs and time. This is demonstrated by a study by Emberey et al. [13]. With regard to mechatronic systems, Mcharek et al. [14] present a method that supports design and optimization with the help of KBE.

3. Research need

Motivated by the persistent drive to improve products and the challenging endeavour to adapt complex technical systems such as mechatronic systems [15], first approaches for their automated adaptation design have been developed to support dealing with the complex interdisciplinary system interrelationships. While numerous approaches address optimization and knowledge-based engineering separately within this context, few approaches consolidate both areas. However, these approaches concentrate either solely on sub-processes in the adaptation process or necessitate a significant amount of time to generate an optimized product, due to a necessary high number of iterations and manual steps in current procedures required to cover extensive changes. Moreover, knowledge from proceeding product development processes is hardly utilized. Thus, the potential of a consistent cross-domain approach for the automation of adaptation design unifying optimization and knowledge-based engineering remains largely unused. To address this problem, this contribution answers the following research question:

> How can the automation of the adaptation design of mechatronic systems be realized through the reuse of knowledge from previous product development cycles?

Thus, the proposed approach aims to demonstrate a consistent procedure from problem identification to the optimized product by automating the adaptation design of mechatronic systems and thereby aims to reduce superfluous iterations for product design in line with requirements. Therefore, it involves a cross-domain optimization by utilizing formalized knowledge from previous product development cycles.

4. Approach for cross-domain optimization of mechatronic systems

The following section provides a conceptual description of the proposed approach consisting of three essential steps, see Figure 1.

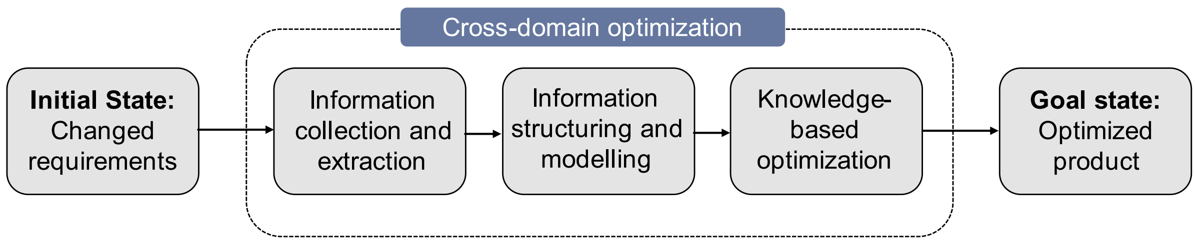

Figure 1: Overview of the necessary steps in the cross-domain optimization approach

In the first step (Chapter 4.1) all relevant information for the optimization are automatically identified and extracted. In the subsequent step (Chapter 4.2) the preparation and structuring of the information in a cross-domain representation as a prerequisite for the optimization is investigated. In the final step (Chapter 4.3) an efficient solution to the complex, cross-domain optimization problem is realized utilizing knowledge from previous product development steps and processes. This approach is developed using an automotive electric window regulator as an example to ensure practical applicability.

4.1. Collection and extraction of domain-specific information

To answer the research question, the information acquisition and availability of information is essential as it forms the fundamentals for the optimization and the subsequent steps. The process for achieving automated information extraction is visualized in Figure 2.

Initially the information needs to be collected and analysed. The objective is to generate a comprehensive overview of all information relating to adjustable mechatronic systems including the structure, the organization as well as the realization. In addition to explicit knowledge, implicit knowledge and undocumented information such as estimates, experience or reasons for decisions should also be included. The identification of possible features of mechatronic systems is of particular significance, as these can be directly influenced by the developer in contrast to the behaviour of the system or the desired characteristics. This includes in particular the identification of all relevant control parameters from the various domains, like material constants.

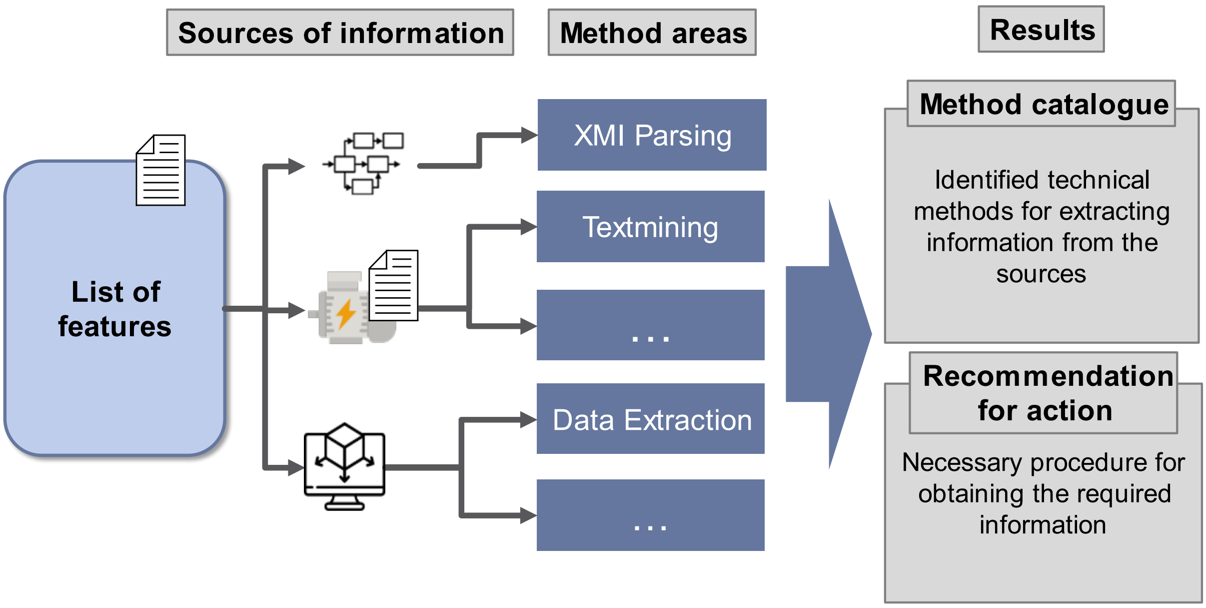

Figure 2: Procedure for collecting and containing information

The intention is to provide the user with a list of all features. To this end, initial existing approaches to feature lists, such as in Pahl and Beitz [16] or VDI 2206 [4], are consolidated into a single comprehensive list and then gradually expanded as well as refined in order to specify adjustable mechatronic systems in detail. Due to the variety of mechatronic systems and specific use cases further refinement on the list can be necessary. This includes the consideration of exemplary application scenarios as well as functionally relevant optimization objectives and constraints. After postulating an overview of the features, it is important to find out where the information can be obtained from. It is important to ensure that the information and boundary parameters in the method catalogue mirror application scenarios as realistic as possible. Although, this cannot be fully achieved as it depends on the use case or development background. In addition, similar information can be found in different documents or formats.

Given that information on features is often scattered and extracting can be time consuming, the next step is to capture and automatically extract all relevant, domain-specific information. In this phase of the process, the developer is supported by a designed comprehensive method catalogue and detailed guidelines for information extraction as part of the adaptation design. The developed feature list, enriched with information sources, serves as the foundation for obtaining all domain-specific information to be considered. Based on this, suitable method areas can now be selected for extracting the necessary information from their sources in accordance with the method catalogue. Clearly defined evaluation criteria support the selection of the method from the catalogue. These criteria can consider aspects such as modelling effort, further use in the development process and usability in the process. Established methods in practice are Text Mining or Data Mining [17]. A comprehensive overview of the methods, including their technical details, is provided in the method catalogue.

4.2. Information structuring and modelling

The extracted information serves as the foundation for structuring and modelling the information. Once the information has been captured, the focus shifts to managing and transforming it into a form that is suitable for optimization. In consideration of the diverse forms of extracted information from the entire mechatronic system, a cross-domain representation is promising for exploration. A number of approaches have already been implemented in industrial practice. One prevalent representation are differential equation systems, which are based on physical equations. Further capabilities are the representation of the system using bond graphs [18] or object-oriented modelling languages [19]. Moreover, system models offer a form of representation for more complex systems [20]. Each of these approaches has specific advantages that depend on the intended use case. A suitable method regarding their suitability and usability for the use case specific cross-domain optimization must be selected based on defined criteria that are placed on the information structure and cross-domain optimization. This can be, for example, the level of detail, change behaviour and continuity. Given the case-specific nature of the selection process, which is based on individual assessment criteria, a generic methodological approach to modelling serves as a useful supplement.

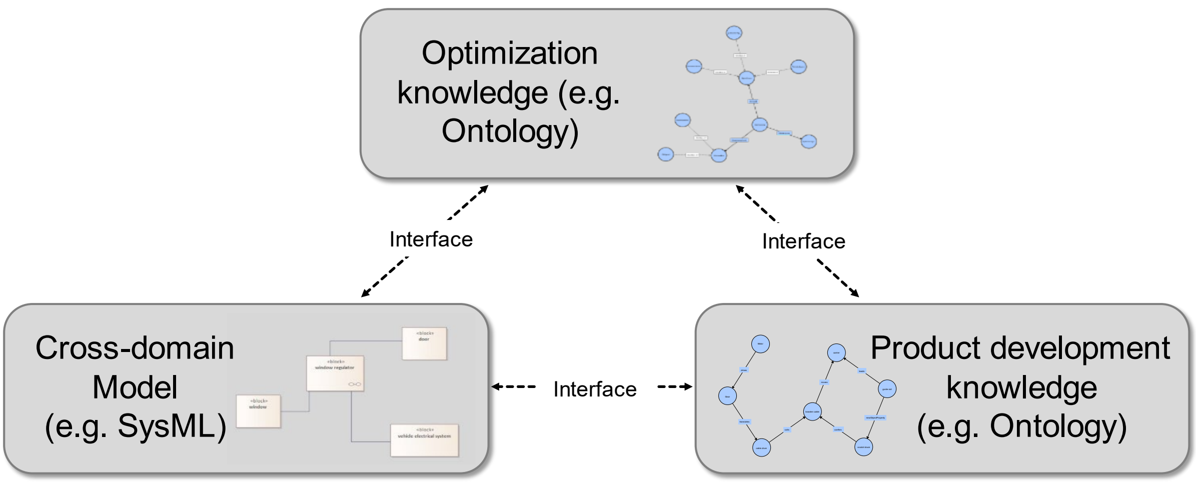

Figure 3: Information structuring and modelling components

The content of the cross-domain model should contain a consistent linking of the collected information as well as a model-based mapping of interdisciplinary interdependencies. It is of paramount importance to map and link the entire cross-domain structure of the system in a single model in order to gain a comprehensive understanding of the system's interrelationships and to be able to control the effects of changes. In addition to the problem-specific modelling in the cross-domain model, superordinate knowledge is mapped in broadly applicable knowledge bases, e.g. with the help of ontologies [21], in order to enable the automation of repeatable tasks, a simplification of the complexity of the subsequent optimization problems and a better incorporation of implicitly acquired knowledge about system interdependencies. Due to the thematic differentiation of knowledge, a subdivision is made into two categories: product development and optimization knowledge. The product development knowledge base contains higher level knowledge pertinent to mechatronic design, including for example design guidelines to be observed as well as knowledge from previous product development steps, such as histories of predecessors or decision criteria for steps. In contrast, the optimization knowledge base stores optimization-specific knowledge, possible applicable optimization algorithms and settings. For this purpose, suitable optimization algorithms will be categorized based on analyses of their usability and potential applications. The knowledge bases in conjunction with the cross-domain model play a pivotal role in the subsequent stage of knowledge-based optimization. In order to achieve this, interfaces between the knowledge bases and the cross-domain model, as illustrated in Figure 3, are necessary. The cross-domain model, in collaboration with the product development knowledge base, is fundamental to precisely define the targeted optimization problem, while the optimization knowledge base is required in order to subsequently define a suitable solution strategy based on the optimization problem. Major attention should thereby be paid to the linking of the data. The decisive factor in this regard is the system level at which they operate and what information is exchanged or utilized.

4.3. Automated derivation and solution of cross-domain optimization problems

The cross-domain model and the knowledge bases created the prerequisites for information availability, structured data and knowledge, so that the relevant information is now available for subsequent parameter optimization.

4.3.1. Knowledge-based optimization

The following section will demonstrate how knowledge-based optimization can be realized, as illustrated in Figure 4. For this purpose, based on strategies for derivation, the interdisciplinary optimization task is derived in the form of constrained simple or multiple optimization problems consisting of objective function(s), constraints and continuous and discrete design parameters with their limits. The interaction between the knowledge bases and the cross-domain model should enable an automated derivation of the optimization problem.

To solve the optimization problem, a suitable optimization strategy will be derived. This depends on a variety of criteria, such as the aspects to be considered as well as system variables. In the context of the optimization strategy, the selection of a suitable algorithm represents a major challenge [22]. In most cases, the optimization problem for mechatronic systems is very complicated due to the interdisciplinary system interrelationships. In addition, the use of behavioural models increases the complexity of the problem due to the numerical effort required to simulate the dynamic, discretized motion behaviour in finite time steps. Therefore, the usage of gradient-free, metaheuristic optimization methods is preferred. The choice of a suitable optimization algorithm and the parameters have a considerable influence on the computing time and performance. Selecting a suitable algorithm and fine-tuning the parameters can increase the probability of finding a global optimum, but never guarantee it completely. For this reason, the aim is to ensure that the solutions meet the requirements for validity, optimality and reproducibility by means of repeat tests and by using common metrics to assess performance.

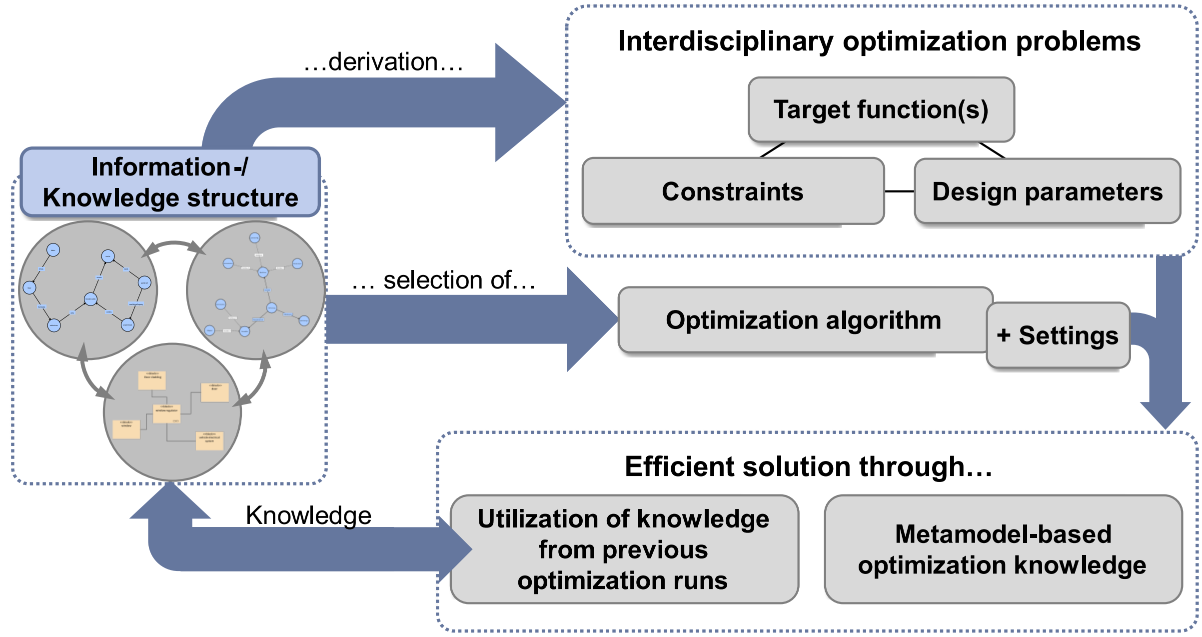

Figure 4: Automated derivation and solution of cross-domain optimization problems

Furthermore, the iterative, chance-based operating principle of metaheuristic optimization algorithms can lead to high computing times. Thus, an efficient, behaviour model-based solution is sought for the generated mathematical optimization problem. Due to the high complexity of such an optimization, methods to increase efficiency should be used in a supportive manner. Various approaches have already proven themselves in practice, which are to be investigated for use in behavioural model-based optimization. In different applications the use of metamodels, such as a successive increase in the performance of simple regression models or artificial neural networks over the course of the optimization process, has proven to be valuable [23]. In addition to metamodel-based optimization strategies, the previously developed knowledge bases and the implicit knowledge gained from intermediate optimization solutions should assist in reducing the complexity of the problem by narrowing down the search space to technically relevant solution variants.

4.3.2. Methods for reusing knowledge

Knowledge plays a fundamental role in all areas of the approach. This initiates with information collection and analysis through the usage of explicit or implicit knowledge and continues throughout the approach in the form of knowledge bases or knowledge-based support during optimization. Furthermore, a lot of knowledge is already generated during the basic development and the new adaptation design, which in many cases expires and is not sustainably reused for future development processes [24].

There is considerable untapped potential in the reuse of knowledge through the utilization of implicitly gained knowledge about relationships between requirements, product features, properties and solution principles, as well as optimization histories and generated metamodels. The approach therefore involves the developed strategies for the targeted utilization of the knowledge generated during adaptation design. It is of particular importance to direct attention to the knowledge generated from optimization histories, which has mostly been discarded to date, because it can provide valuable insights into the component or system behaviour, and contributes to the simplification of the effort involved in future optimization runs. The focus of optimization is typically on the results, although fundamental implicit knowledge is also generated, which is often overlooked. This knowledge can be derived from implemented changes, as well as from interim solutions that are not optimal, valid or invalid. However, explicating this knowledge is a challenging task that is the focus of many research projects. Therefore, investigated appropriate methods should be utilized to make implicit knowledge available for future process steps. By linking and thus continually expanding the knowledge bases a more detailed support and improvements for further adaptation designs is intended to achieve.

5. Application

The steps of the proposed approach are subsequently applied for an adaptation design scenario of an automotive electronic window regulator, see Figure 5. Therefore, it is assumed that the requirements and derived optimization targets as well as constraints for a window regulator change due to new regulations. This might require to optimize the closing movement of the window under load in a new specified time, whereby the motor speed is identified as elementary among other characteristics. Therefore, the proposed **method catalogue** helps to **automatically extract the relevant information** on the features, such as the motor speed from the data sheet, e.g., by using Data Mining. Due to the different forms of extracted data and with regard to the upcoming optimization, the interdisciplinary interrelations and the consistent conjunction between the information's are mapped in a **cross-domain SysML-model**. In addition to the cross-domain model, two **knowledge bases**, which are provided by the approach, are expanded as part of the application to include product and optimization target-specific information. The utilization of knowledge bases serves to enhance the degree of automation and reduce complexity. Through the connection of the product development knowledge base and the cross-domain model it becomes clear that, in addition to the motor, the weight of the window pane also had a significant influence on the optimization objective.

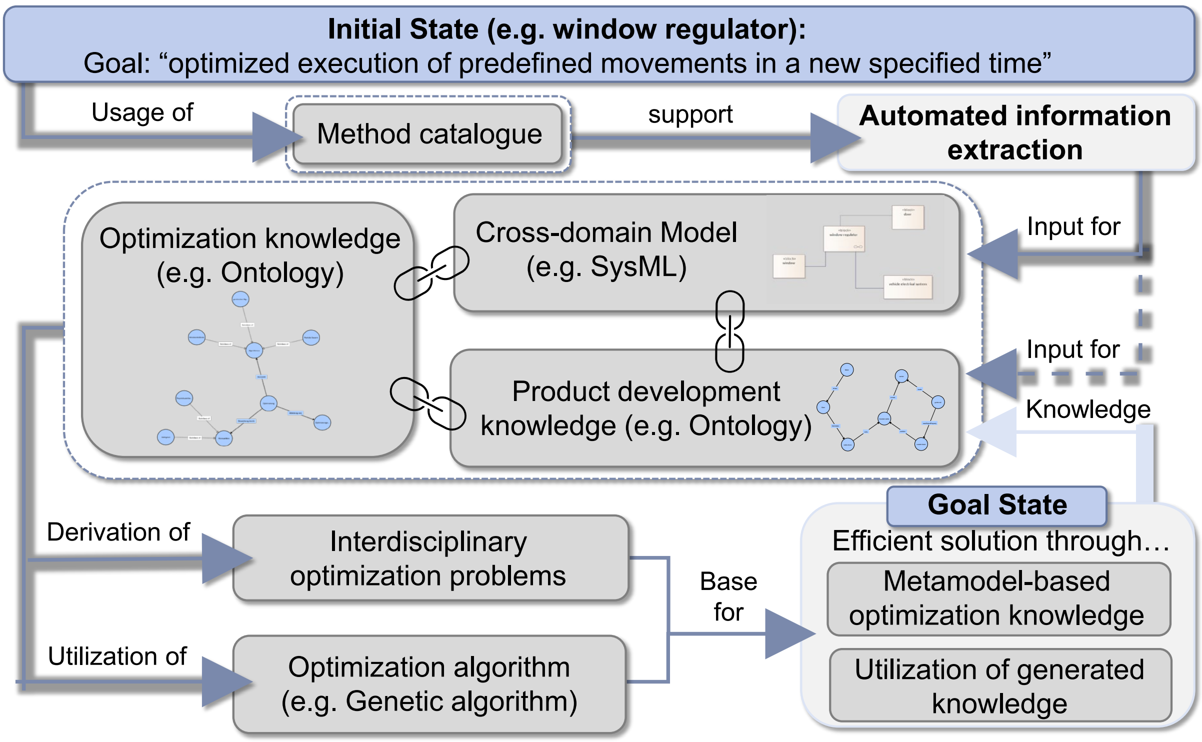

Figure 5: Application steps of the knowledge-based approach to cross-domain optimization

Based on this information, the **multi-domain optimization problem**, including the constraints, can be derived largely automatically. To solve the complex cross-domain optimization problem, an **optimization algorithm**, such as the genetic algorithm, is recommended from the optimization knowledge base based on the defined criteria and subsequently applied to solve the problem. Due to the high complexity of the problems, usually long computing times result during the optimization in order to find the best possible solution. **Metamodel-based optimization strategies**, like the usage of artificial neural networks over the optimization process, provide a remedy and reduce computing times. In addition, the efficiency and quality of the optimization results is increased by reusing product **development knowledge from previous design iterations and existing optimization histories** in from of a restriction in the parameter scope. By applying this approach, the product developer will be capable of mastering the complexity and achieving a reduction in the required closing time with a high degree of reusability of the system components in a shorter development time.

6. Conclusion and outlook

Based on the gaps and potentials from the current state of the art on the automated adaptation and optimization of mechatronic systems, a knowledge-based approach was proposed. This approach addresses the primary challenges associated with the development of mechatronic systems, complexity and time-consuming mostly due to unnecessary iterations. The approach is particularly characterized by its consistent procedure with a high degree of automation and the integration and reuse of knowledge. The high degree of automation is achieved through the utilization of automation processes in the information procurement process, with the objective of reducing the high effort involved in obtaining information and the support of automation processes in the definition and solution of optimization problems in order to contribute to the most efficient optimization possible. In addition to the automation of sub-processes, the incorporation of knowledge throughout the process significantly enhances its performance. Combining knowledge and model-based cross-domain representation enables the complexity in terms of interrelationships and potential effects to be mastered, which leads to the avoidance of errors. Furthermore, the reuse of knowledge from previous product development stages and processes confers a significant advantage, as it enables the avoidance of unnecessary tasks and reduces the complexity of the problem, thereby increasing the efficiency by avoiding unnecessary optimization iterations.

This approach represents a further step towards the efficient and automated development of an optimized mechatronic system. Nevertheless, the approach has thus been confined to a concept whose further development is outstanding. In this context, the approach still leaves interesting points to be investigated. One leverage point could be to examine the impact of integrating formalized knowledge from predecessors and optimisation histories on the optimized product. The objective would be to evaluate the extent to which limited information availability affects the subsequent outcome of the project.

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