Design under Uncertainty – Model-Based Determination of Uncertainties in the Application of Reused Components

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Abstract

The application of reused components introduces significant uncertainties regarding their specifications, condition, and behaviour. This paper presents a model-based approach for identifying such uncertainties using MBSE with SysML. By modelling different component instances and aligning top-down and bottom-up perspectives, the identification of both endogenous and exogenous uncertainties can be supported. These uncertainties are classified along three dimensions: nature, level and location. The approach is demonstrated through a use case involving the integration of a reused electric motor into a rover platform. The goal is to provide a basis for developing suitable uncertainty mitigation strategies in early-stage design.

Keywords

Uncertainties, MBSE, Reuse

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1. Introduction and motivation

The increasing demand for sustainable solutions is influencing product design processes across industries. While traditional drivers such as functionality, performance, and cost efficiency remain central in product design, sustainability objectives that span the entire product life cycle are becoming increasingly important. This shift has prompted the integration of sustainability considerations into the earliest stages of design, where decisions concerning life cycle strategies, system architecture, and material selection have a significant influence on a product’s environmental impact. To support this integration, a variety of methods and tools have emerged. Eco-Design provides guidance by helping engineers to define environmental requirements in the early design phases [1]. Several Design for X (DfX) methods have been developed to address specific life cycle-related product properties, such as disassembly, recyclability, maintainability, and modularity [2]. Building on this development, the concept of Circular Economy (CE) is introduced as a key enabler. Within the CE paradigm, value preservation is pursued by closing, narrowing or slowing resource loops through strategies such as repurpose, remanufacturing, refurbish, repair and reuse, commonly referred to as R-strategies [3], [4], [5]. These strategies are increasingly considered during the design phase to ensure that products, components or even materials retain value over multiple life cycles. Among them, reuse is often considered as the most resource- and energy-efficient strategy [6]. The previously stated DfX methods have been extended to better align with CE strategies, as demonstrated by the integration of durability and circularity considerations into DfX frameworks [7]. This reflects a prescriptive design approach, where the product is planned from the beginning to follow predefined life cycle strategies. For example, components may be designed according to “Design for Disassembly” guidelines to facilitate future recycling. Similar principles apply to other R-strategies, such as reuse and remanufacturing, where products are intentionally designed to be recovered and reintegrated. This paper, however, focuses on a reactive design perspective, in which products are developed using components that have already been in use and might not have been originally intended for future reuse. In such cases, engineers must work with components whose properties, such as geometry, material integrity, or functional behaviour, may have changed over time due to prior usage, degradation, or other life cycle processes. Critical information about these components is often unavailable due to a lack of monitoring, insufficient life cycle data management [8] and insufficient insight into the physical components. This introduces significant uncertainty into the design process and requires methods to assess, manage, and reintegrate such components effectively. As a result, design decisions must be made despite limited knowledge about a component’s current state, functional reliability, or compatibility with the new product. Figure 1 illustrates the relationship between two distinct product life cycles: the used product, from which a component is to be recovered, and the new product under design, into which this component is intended to be integrated. When a used component is considered during the design of a new product, certain information proves highly valuable for evaluating its suitability and supporting its reliable integration. This includes (1) the used product specifications to understand the component’s intended function and constraints, (2) data from the use phase to assess how the component has been degraded over time, and (3) condition data obtained during disassembly or inspection to evaluate its current state. In many cases, this information is incomplete, unavailable, or inconsistently documented, which increases uncertainty and complicates decision-making during the design of the new product with the reused components.

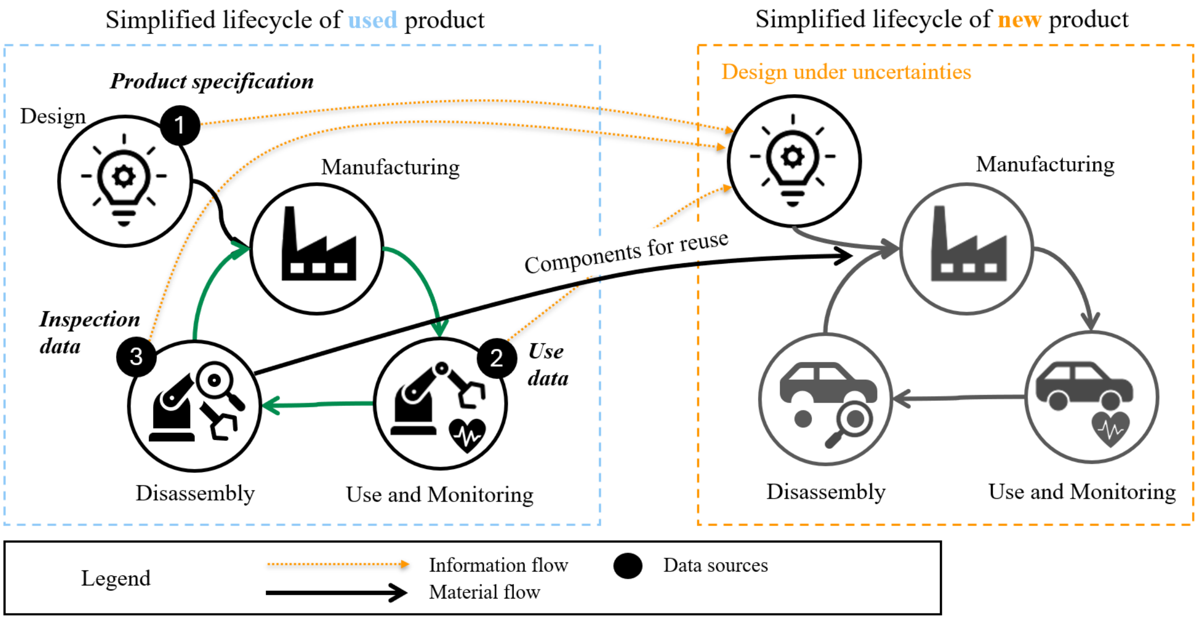


Figure 1: Simplified life cycle of the new and used product with indicated sources of relevant information

To support the integration of reused components under uncertain conditions, this research investigates how Model-Based Systems Engineering (MBSE) can be applied to structure and manage the associated uncertainties. This paper explores how selected modelling constructs in MBSE can be utilized to aid in the identification and classification of uncertainties that arise during the reuse of components in new product designs (Figure 2). MBSE offers a formalized modelling environment that allows for the traceable representation of component requirements and specifications. By embedding available information within system models, MBSE can support the identification of gaps between specification and as-is data, as well as their resulting uncertainties.

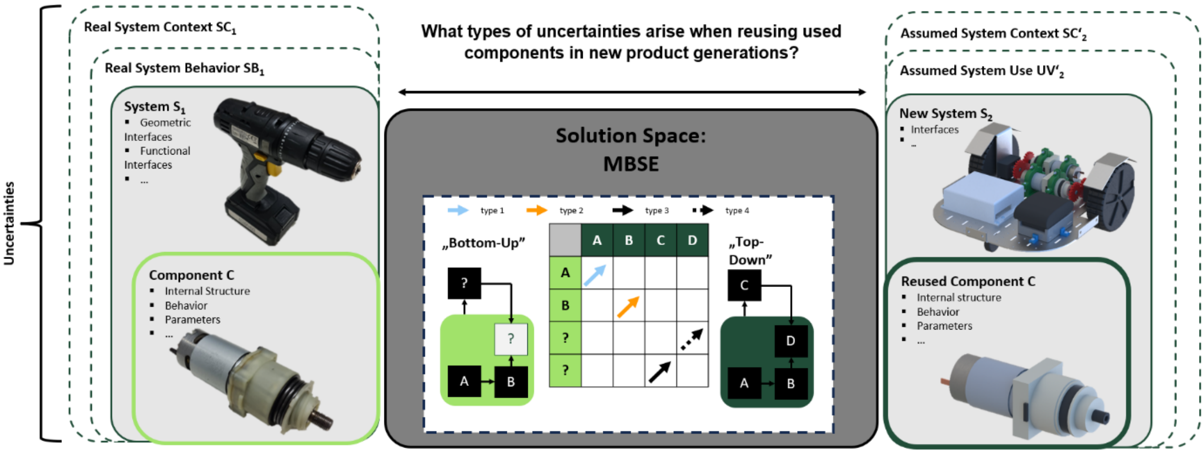


Figure 2: Simplified illustration of the proposed approach for identifying uncertainties

By identifying and classifying uncertainties early in the process, this approach supports more informed decisions and facilitates the reliable integration of reused components. The overall goal is to provide a structured basis for developing uncertainty mitigation strategies in later design stages. These may include the use of margins, targeted design choices, verification, and test procedures. However, mitigation strategies are not discussed in this paper.

2. Research objective

When reused components are integrated into new products, engineers are often faced with uncertainties that do not typically occur in conventional product design. In contrast to newly manufactured components, reused components require design decisions to be made with limited or imprecise information. This research aims to systematically identify and classify such uncertainties in the context of reactive design. It investigates how MBSE approaches can support the structured identification and management of key drivers and the assessment of uncertainties when reusing components. The objective is to provide a formal basis for uncertainty mitigation strategies. Against this background, the research questions of this paper are formulated as:

R.Q.1: What types of uncertainties arise when reusing components in new products under design, what are the causes and drivers for these, and how can they be classified?

R.Q.2: How can information management based on MBSE be used to identify these uncertainties in the early phases of product design?

The next section provides an overview of related research, including uncertainty in engineering design, reuse as an R-strategy, and application of MBSE to support information management in the context of CE. The classification of uncertainties is introduced in section 4. Section 5 presents the proposed method for uncertainty identification and classification. Section 6 presents a case study demonstrating the method's application. The findings are analysed in section 7 with respect to the research questions. The last section discusses limitations and directions for future work.

3. State of the Art

3.1. Reuse of Components

According to Kirchherr et al. [5], there are various R-strategies that aim to extend the service life of products and their components. These strategies include repurpose, remanufacture, refurbish, repair and reuse. The importance of these strategies with regard to circularity is increasing in the mentioned order. There are often disposed products that are no longer functional as a whole, but still contain functional components. There are also products that still have functional components, but these are no longer needed in the current life cycle of a product and can therefore be used in new products. Against this background, a closer look at the R-strategies refurbish or repair for these components does not appear to be necessary. After all, refurbish describes the reconditioning of an old component and repair describes the repair of defect components with the aim of restoring the original function. [5] This paper therefore focuses on the R-strategy of reuse. The reuse of components can be divided into the process steps of recirculation, disassembly, testing, cleaning, refurbishing and reintegration. However, there are different definitions of the term reuse in the literature. The term is sometimes referred to as cannibalization or understood as part of the R-strategy of remanufacturing. The reuse of used components poses various technical challenges. [9] For example, Conti and Orcioni [10] emphasize that components or products in the previous lifecycle must be preserved in the best possible way in order for reuse to be effective due to a long remaining lifetime. These aspects are particularly relevant if components from older products are to be reused in new products. In addition, the energy efficiency of the components plays a decisive role in their integration into new products under design. Cooper and Gutowski [11] show that energy-operated components are less suitable for reuse than non-energy-operated components, as poorer energy efficiency usually has a negative impact on environmental benefits. From a design perspective, the high number of variants and the increasing manufacturer diversity of some components pose a challenge [12]. This is due to the fact that each component has hundreds of technological properties that need to be assigned to a suitable application [13]. All of these core challenges are associated with uncertainties, the classification of which is discussed in more detail in the following chapter.

3.2. Uncertainties and existing Frameworks

McManus et al. [14] emphasize that different types of uncertainty can lead to either risks or opportunities. Classifying uncertainty is therefore essential for supporting appropriate design decisions, such as the selection of suitable mitigation strategies. This section provides an overview of these dimensions and forms the foundation for the classification in this paper. A framework to structure uncertainty is provided by Walker et al. [15]. It is based on three key dimensions: location, level, and nature. These dimensions help to determine where uncertainty arises, how much is known about it, and what type of uncertainty is present. The location of uncertainty refers to where it occurs within the product. According to Walker et al. [15], uncertainty can be found in the system context, structure, input data, parameters, or outputs. Kreye et al. [16] refine this classification for engineering design by proposing four types of uncertainty manifestation: context, data, model, and phenomenological. In this formulation, manifestation is introduced as an additional layer that captures how uncertainties become visible in different stages of the design process. It complements the core dimensions defined by Walker and offers a more practical lens for applying uncertainty classifications in engineering practice. In sustainability-related research, data uncertainty has been extensively studied and further classified (e.g. in the context of life cycle assessment (LCA)). Formal modelling approaches have also been developed to deal with these kinds of uncertainties [17]. Further distinctions regarding the location of uncertainties are made by De Weck and Eckert [8], who differentiate between endogenous uncertainty, which arises within the system and can often be influenced by design decisions, and exogenous uncertainty, which stems from external sources and must typically be anticipated rather than controlled. The level of uncertainty describes the degree of knowledge about a system parameter or behaviour. Walker et al. [15] present this as a continuum ranging from full certainty to complete ignorance. Similarly, McManus et al. [14] frame this concept using the terms known unknowns and unknown unknowns. The nature of uncertainty concerns its underlying cause. Epistemic uncertainty stems from incomplete knowledge and is, in principle, reducible through further investigation. In contrast, aleatoric uncertainty results from inherent variability and is generally irreducible [18]. This distinction is fundamental across uncertainty frameworks used in product design. In mechanical engineering, Antonsson and Otto [19] identify probabilistic uncertainty as equivalent to aleatoric uncertainty, while imprecision reflects epistemic uncertainty.

3.3. Model-based Systems Engineering in the context of Circular Economy

To support the objective of identifying uncertainties in component reuse through MBSE means, the following paragraph examines how MBSE is currently applied in the design of circular systems. Methods and frameworks for supporting circular product design have increasingly been explored in conjunction with MBSE. As highlighted in a recent review [20], MBSE enables the integration of circularity considerations into system models. One notable contribution [21] introduces the concept of Circularity Measures (C-Measures), which translate high-level R-strategies into concrete, product-specific design actions. These measures are embedded in MBSE meta models to ensure that circular principles such as reusing, remanufacturing, and recycling are systematically implemented. In contrast to this research, individual CE strategies have been explored in less detail. In regard to remanufacturing, research [22] has initially focused on the MBSE modelling of such products and on deriving specific modelling requirements. In conclusion, MBSE enables integration of circularity goals into product design and improves the management of the increased complexity resulting from multiple product configurations and life cycles.

4. Classification of uncertainties in context of reactive design

The classification of uncertainties was developed through a combination of literature analysis and empirical investigation, grounded in the work presented in the state of the art. The aim of the classification is to support the structured identification and representation of uncertainties in the context of reactive design. The identification of uncertainty classes must support early design-stage decisions despite incomplete data, capture both uncertainty from prior usage and design specification. Existing classifications do not fully address this unique case of reusing components in the new products under design. The proposed classification is based on three core dimensions: nature, level, and location, shown in Table 1.

Table 1: Classification of uncertainties in the context of reactive design

Uncertainty dimension	Uncertainty class	Description
Nature	Lack of data	*Gaps in knowledge regarding product structure, behaviour and/or parameters.*
	Data variability	*Unknown probability distribution or variation of property / parameter values.*
Level	Black-box	*Unknown data at the subsystem (component) boundary (e.g. item-, energy- or information-flows, interfaces).*
	White-box	*Unknown data inside the subsystem (component) boundary (e.g. structure or behaviour).*
Location	Endogenous	*Unknown original specification of the component for reuse.*
	Exogenous	*Unknown change in component state during use phase.*

The nature of uncertainty is distinguished as either incompleteness, where data is missing or undocumented, or variability, where data exhibits probabilistic spread, often amplified by degradation during prior use. The level dimension differentiates between black-box and white-box uncertainties. Black-box refers to limited data about a component's structure and behaviour at the modelled subsystem boundary, focusing on interfaces, input-output parameters. On the other hand, white-box data includes internal structure and behaviour. This distinction aligns with modelling approaches like MagicGRID [23]. The location dimension refers to the source of uncertainties with regard to the product and its context. Endogenous uncertainties are tied to the component's "as-specified" state and arise from incomplete, ambiguous, or outdated information in the original design documentation, such as missing tolerances, inconsistent interface definitions, or underspecified behaviour. In contrast, exogenous uncertainties emerge from the component's use phase or other later stages in the product life cycle. These include wear, degradation, environmental effects, or damage during disassembly, all of which can alter the component from its intended design state. Such influences lead to a divergence between the "as-specified" and the actual "as-is" state, which must be evaluated during reuse.

5. Method

The method details how an MBSE approach can be used to systematically identify uncertainties in the reuse of components. It is intended for use during standard MBSE practices, particularly in the subsystem definition and design space exploration phases. Once the required subsystem has been defined, the method supports the evaluation of potential component reuse cases by identifying and analysing relevant uncertainties. The outcome of this process is a structured overview of knowledge gaps, which serves as a foundation for subsequent design decisions. By highlighting areas of limited understanding, the method facilitates more informed and deliberate choices grounded in knowledge gap awareness. To achieve this, two perspectives were modelled, both using the SysML notation within a MBSE tool environment [24]. First, a top-down requirement specification was formulated to represent the target properties and constraints of the new product under design. These requirements were further refined, and the corresponding system elements (structure and behaviour) were modelled in accordance with standard MBSE practices. The top-down modelled elements are marked as “as-required” and thus describe relevant aspects of the requirements for the components to be reused. This marking (see also Figure 3) forms the starting point for later comparison with the „as-is“ descriptions. Alongside the “as-required” elements, a bottom-up description of the components for reuse was developed and marked with the term “as-is”. The modelled “as-is” elements include the available data of the component, such as the actual condition, performance, and possible historical use. The alignment of the modelled top-down and bottom-up views enables the systematic identification of uncertainty types. The MBSE model is intended to support the identification of different types of uncertainties by enabling a structured alignment between the required component properties and the known "as-is" properties of the component for reuse. This alignment allows uncertainties to be revealed where required properties are unknown, only partially known, or mismatched with the component's current state. In the MBSE environment, this alignment is realized through assignments, such as allocation relationships. In the present approach, two SysML concepts are used to support this modelling.

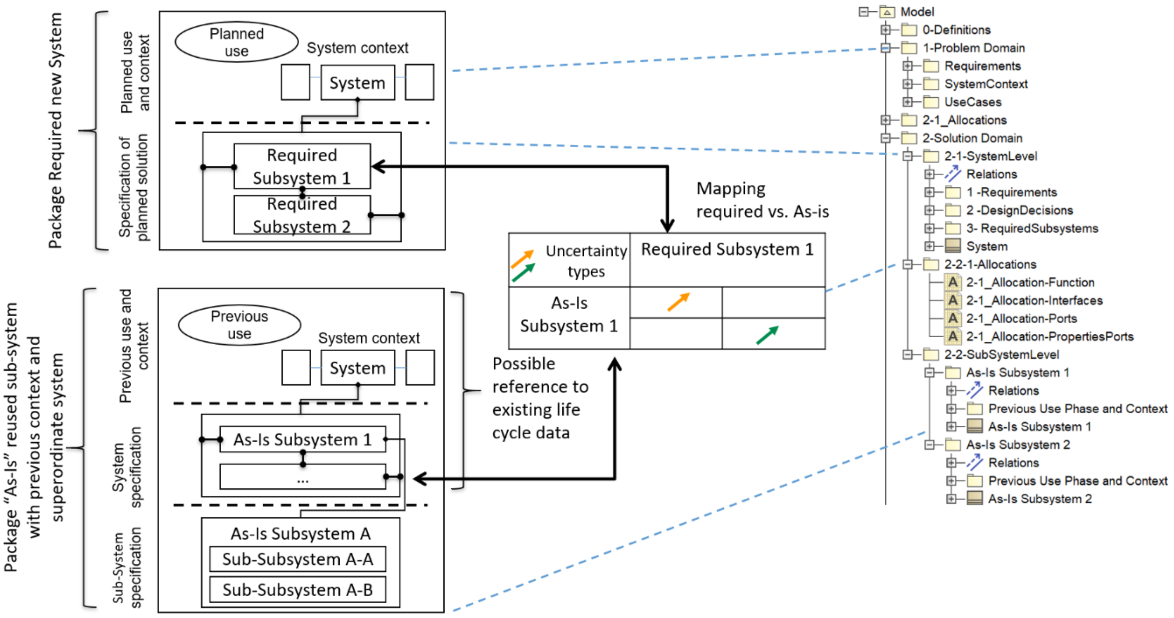
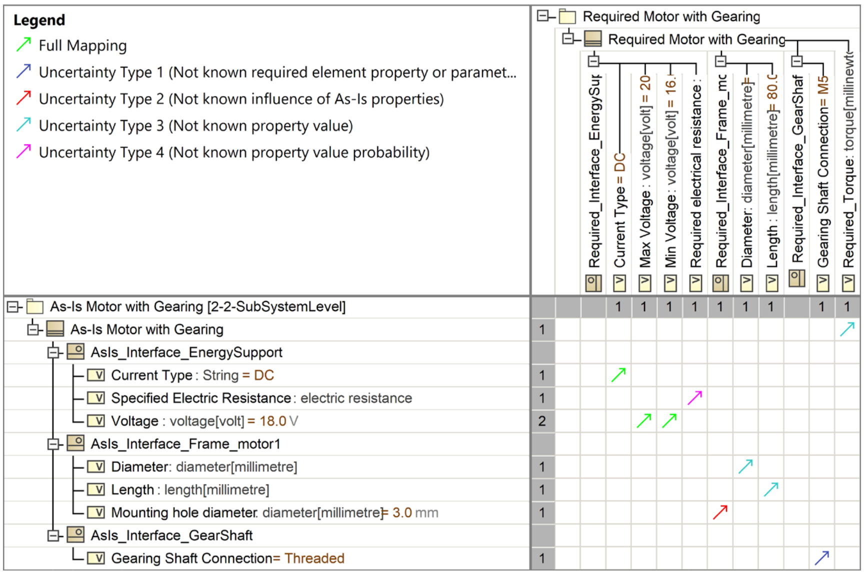


Figure 3: Model structure with regard to the mapping process

First, SysML models are based on a metamodel that can be extended with stereotypes. These can be used to create specific elements for required and “as-is” properties. This enables the specification of the product under design, the required components, and the known As-Is state of the components. In addition, specific stereotypes are useful for assignments to describe how the required properties are covered by the known “as-is” properties. This approach enables uncertainty types to be explicitly captured through specialized allocation relationship stereotypes, as shown in the legend of the case study matrix in Figure 4. Due to the varying dimensions and theoretical nature of the uncertainty classes, the types used in the mapping were defined with practical applicability in mind to support practitioners. Each defined uncertainty type can be linked to a corresponding dimension from the uncertainty classification. For example, uncertainty type 4 (Not Known Property Value Probability) reflects the variable nature of a parameter influenced during the product's use phase, which is considered an exogenous source of uncertainty. When information is missing on either side of the mapping, a connection is made to a higher-level element using one of two defined relationships. In cases where the "as-is" parameter is not required, but may still exert an influence, this is categorized as uncertainty type 2 (see Figure 4) and may warrant an influence analysis, which is often the case when endogenous, white-box level data is not available. Alternatively, if the required parameter is not known to exist in the reused component, this is classified as uncertainty type 1. Uncertainty type 3 captures situations involving an endogenous lack of information. The second SysML concept used is the structuring of the model with packages. Packages allow modular and potentially replaceable structures to be created for the required overall system, its components, and the "as-is" components (modelled as subsystems). Further structuring is possible within these packages. For example, the model can distinguish between the problem and solution space of the required product and represent the previous product context or higher-level system relevant to the reused component (see Figure 3).

6. Case Study

In order to demonstrate the proposed method, a rover platform is being developed with the goal of reusing components from other products. For this purpose, a used and non-functional cordless screwdriver has been selected as the used product. The electric motor extracted from the cordless screwdriver (Figure 2) is being considered for integration into the new product. The rover platform, a delivery vehicle for university teaching made of purchased or additive-manufactured parts and reused electric motors, serves as a case study demonstrating how the proposed method evaluates if a used component meets new performance requirements despite original-use uncertainties.



Legend
↗ Full Mapping
↗ Uncertainty Type 1 (Not known required element property or paramet...
↗ Uncertainty Type 2 (Not known influence of As-Is properties)
↗ Uncertainty Type 3 (Not known property value)
↗ Uncertainty Type 4 (Not known property value probability)

Required Motor with Gearing
Required Motor with Gearing

			Required_Interface_EnergySup	Current Type = DC	Max Voltage : voltage[volt] = 20	Min Voltage : voltage[volt] = 16.	Required electrical resistance :	Required_Interface_Frame_mc	Diameter: diameter[millimetre]=	Length : length[millimetre]= 80.0	Required_Interface_GearShaf	Gearing Shaft Connection= M5	Required_Torque: torque[millinewt
As-Is Motor with Gearing [2-2-SubSystemLevel]				1	1	1	1	1	1	1		1	1
As-Is Motor with Gearing	1												↗
AsIs_Interface_EnergySupport													
Current Type : String = DC	1			↗									
Specified Electric Resistance : electric resistance	1						↗						
Voltage : voltage[volt] = 18.0 V	2				↗	↗							
AsIs_Interface_Frame_motor1													
Diameter: diameter[millimetre]	1								↗				
Length : length[millimetre]	1									↗			
Mounting hole diameter. diameter[millimetre]= 3.0 mm	1							↗					
AsIs_Interface_GearShaft													
Gearing Shaft Connection= Threaded	1											↗	

Figure 4: Excerpt alignment of interface parameters of the electrical motor with gearing

Once the electric motor is extracted, all information regarding its properties is initially uncertain. However, the type plate on the motor housing enables identification of the component and retrieval of a traceable data sheet. This specification serves as the basis for defining the initial "as-specified" model and helps to reduce early-stage endogenous uncertainty by providing key parameters such as rated power and voltage. Requirements for the rover platform have been derived from its intended use cases, and the relevant subsystems have been modelled to fulfil these requirements. These elements are represented in the top part of the matrix shown in Figure 4. and include interface specifications and their associated parameters, such as voltage, torque, and geometric dimensions. From the perspective of the reused component, the evaluation draws on both available specification data and observed physical characteristics, corresponding to the “as-specified” and “as-is” representations introduced earlier. In contrast, refer to properties determined through direct inspection during disassembly and physical evaluation of the used component (see Figure 1). These two perspectives represent the intended design state and the actual condition of the reused component, respectively. A mapping is then conducted between the rover platform model and the reused electric motor model using the previously defined relationships. The scope of this case study was limited to the interface property mapping. An excerpt of the results is shown in Figure 4. The matrix representation highlights how many required properties are known and fully mapped, and how many remain subject to uncertainty. Based on this representation, a summary should be formulated to support the development of a plan for further investigation and appropriate mitigation strategies.

7. Discussion and conclusion

This work addressed the challenge of designing under uncertainty when reusing components from existing products. A model-based approach was proposed, integrating uncertainty classification and a mapping process for the purpose of identifying uncertainties as a basis for further planning. The research addressed two main questions related to the reuse of components in early-stage product design. The first focused on identifying and classifying the types of uncertainties that occur in this context. The proposed approach demonstrated that uncertainties can be organized based on three dimensions: nature, which includes uncertainties such as the lack or variability of data; level, capturing the degree of knowledge available, such as black-box or white-box representations; and location, referring to whether the uncertainty is endogenous or exogenous. The second question explored how MBSE can support the identification of these uncertainties. By modelling both the required and available “as-specified”, “as-is”) subsystems and linking them through a structured alignment process, the method provides a clear overview of uncertainties. This supports better-informed decisions and early planning for uncertainty mitigation. The case study involving the design of a rover platform demonstrates the feasibility and practical value of the proposed method. It is illustrated how structured modelling can make uncertainties explicit by distinguishing between known, unknown, and partially defined parameters, thereby guiding targeted action in early-stage design. One limitation of the case study was the absence of historical usage data, which restricted the ability to assess exogenous uncertainties in depth. Future case studies should incorporate such data to enable a more comprehensive analysis of how prior usage influences the mapping process and the nature of uncertainties encountered. Furthermore, applying the method to more complex products will be essential to evaluate its scalability and general applicability. Future research shall focus on the integration of monitoring data of used components and uncertainty mitigation strategies into the design process, aiming to support more robust and proactive reuse decisions in engineering design.

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