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Reducing uncertainties in data & information - an ontological approach to support satellite development projects

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ABSTRACT: The evolving needs of customers and stakeholders necessitate the collaboration of diverse system elements within a cyber-physical, socio-technical network. Such Sociotechnical systems are characterized by numerous complex interdependencies as well as by endogenous and exogenous influences. A key issue that developers must address is the mitigation of data and information uncertainties. This paper introduces an ontological approach to facilitate the identification and mitigation of uncertainties in data and information within a model-based methodology for satellite development projects. The work outlines the results of preliminary studies forming the foundation for this ontological concept. The proposed approach comprises an overarching General Ontology, complemented by a Uncertainty and Structure Ontology, creating a framework for uncertainty management in satellite development.

KEYWORDS: ontologies, systems engineering (SE), product modelling / models, model based systems engineering, satellites

1. Introduction

In the development process of technical products, uncertainties pose significant challenges that can impact project success. These uncertainties often arise from conscious or unconscious knowledge gaps or definitional ambiguities. Panusch et al. (2023), building upon the discourse of Walker et al. (2003) on uncertainties, emphasize that identifying and reducing such uncertainties is of great importance in the development of innovative products. This is particularly crucial as projects subject to numerous unpredictable uncertainties face a high risk of failure (Lindemann, 2016).

Satellite missions, in particular, often grapple with uncertainties due to their inherent complexity (Feldhacker, 2011) and the challenging context in which they operate and interact with other contextual partners. Current research efforts focus on both the early identification of uncertainties and their explication and systematic consideration in models. Gräßler et al. (2021) and Inkermann (2022) highlight the potential of Model-Based Systems Engineering (MBSE) methods, languages, and tools in this regard. Similarly, Husung et al. (2021) emphasize the possibility of uncovering errors in system descriptions through the application of defined analysis methods.

Building on this motivation, we are developing a methodology for the process-accompanying development and maintenance of holistic system models to support the evolution of data and information and their flows in the development process of satellite projects. The focus lies on identifying and mitigating uncertainties inherent in data, information, and their flows, as well as facilitating knowledge generation throughout the development process. However, for models to effectively serve their purpose, they require precise semantics to ensure coherence, shared understanding, traceability, and logical inference (Bermejo-Alonso et al., 2016). Therefore, ontological analysis within a domain becomes an essential complement to modeling. The categorization process inherent in ontology development supports information acquisition (Wang et al., 2001), thus promoting knowledge generation. Devedzic,

(2002) posits that the main goal of ontology development is to facilitate knowledge sharing and reuse, as well as to elucidate the knowledge structure within a domain. Moreover, ontology-based frameworks play a crucial role in reducing semantic ambiguity in conceptual models (Mordecai et al., 2021) thereby contributing to the reduction of uncertainties. Consequently, the authors formulate the following research question addressed in this paper:

RQ: What ontological concept is suitable for supporting the identification and mitigation of uncertainties in data and information within the framework of a model-based approach for satellite development projects?

However, preliminary investigations are necessary to establish a foundation for answering the research question. Therefore, the following questions need to be addressed initially:

- Are there existing ontologies in the field of satellite development projects aimed at identifying uncertainties in data, information, and their flows by supporting system modeling?
- What method is suitable for developing a domain- and task-specific ontology?

This contribution sets the stage for a comprehensive exploration of ontological approaches to uncertainty reduction in satellite development projects, promising valuable insights for both the aerospace industry and the broader field of Systems Engineering. The contribution is structured as follows:

Section 2 outlines our research approach, addressing preliminary questions regarding the existence of ontologies in satellite development projects and methods for ontology development. Section 3 provides a concise explanation of ontologies and gives a brief introduction to uncertainties. Section 4 presents the state of the art, while Section 5 presents the preliminary investigations. Section 6 presents our proposed ontological concept for identifying and reducing uncertainties in satellite development projects. Finally, Section 7 summarizes our findings and provides an outlook for future research directions.

2. Research approach

To address the two preliminary questions, we conducted a systematic literature review, drawing inspiration from the works of Yang et al. (2019), Michalides et al. (2023), Qaswar et al. (2023), and Nicklas et al. (2023) for developing our selection process. We employed the six-step process methodology outlined by Machi & McEvoy (2016) as our methodological framework.

A search string comprising the keywords “Ontology”, “satellites”, “satellite missions”, and “satellite development” was formulated and applied to the Scopus database. Scopus was chosen due to its rigorous quality control for indexed content, wide availability in academic institutions, and extensive coverage of technical and engineering literature particularly relevant to our field of research. The scope was delimited to Computer Science, Engineering, and Earth and Planetary Sciences, with no constraints imposed on publication dates. This initial search yielded 674 articles, which were subsequently evaluated for relevance to the preliminary questions through a multi-step selection process, as illustrated in Figure 2. Articles were considered eligible if they pertained to one or more of the following subject domains, documented in Figure 1.

Subject domain	Description of…
SD1	a domain-specific ontology
SD2	a cross-domain ontology
SD3	the use of an ontology/ontologies
SD4	a procedure for ontology development
SD5	a tool or aid for ontology development
SD6	relevant mechanisms for ontology development
SD7	the basics of ontology

Figure 1. Subject domains for the Literature review

In the final step, we expanded the literature search to include an in-depth, recursive tracing of sources. This broadening of the source pool resulted in the identification of 72 literature sources, all of which were analyzed in detail to address the preliminary questions.

The outcomes of the literature review are delineated in Section 4, serving as the foundational input for shaping the preliminary study presented in Section 5, which in turn forms the basis for the development of an ontological concept to answer the research question.

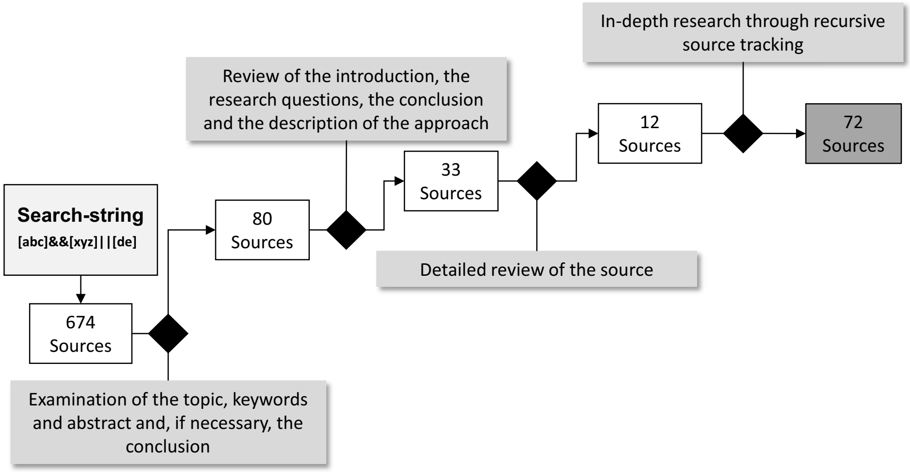

Figure 2. Literature selection process

3. Background

3.1. Ontologies

The term "ontology" has been extensively addressed in numerous works, providing a comprehensive description. The probably most frequently cited definition of the term ontology is the following variant from Gruber, (1993): *An ontology is an explicit specification of a conceptualization.*

Here, a conceptualization is described as a streamlined, purposeful, and simplified representation of reality. Depending on the focus of this conceptualization, distinctions can be drawn among application ontologies, domain ontologies, generic ontologies, and representational ontologies (Guarino, 1997). According to Portelli et al. (2019), they can be organized into several layers. For instance, upper-level ontologies embody an abstract frame of reference that is independent of any specific application domain. Mid-level ontologies, on the other hand, furnish vocabulary tailored to particular application domains, while lower-level ontologies, also known as domain ontologies, offer vocabulary specific to individual use cases. This concept fosters the reusability of individual ontologies (ibid). For further information regarding the explanation of ontologies we refer to Schmalenbach (2013), Mizoguchi (2004) and the handbook on ontologies (Staab & Studer, 2009).

3.2. Uncertainties

The term "uncertainty" encompasses a broad spectrum of ideas and concepts, pointing on aspects as ambiguity, lack of certainty, and unknown or un-knowable elements (Thunnissen, 2003). In the context of product development, De Weck et al. (2007) view uncertainty as encompassing both the potential for erroneous assumptions and the presence of unknown factors influencing future product success. This is particularly relevant in satellite development, where complex systems and novel technologies often introduce significant uncertainties. For this paper, we focus on epistemic uncertainties, which can be mitigated through problem-related knowledge discovery (Walker et al., 2003) as opposed to aleatory uncertainties, which are not systematically reducible.

Drawing from the conceptualization by Paetzold (2022), we understand uncertainties as encompassing discrepancies, gaps, inconsistencies, and incompleteness within data and information (D&I) and their corresponding flows. Gaps include missing connections and relationships between different D&I, as well as incomplete system context definitions. Incompleteness refers to available but insufficiently described D&I, such as missing properties within defined flows between system elements. Inconsistencies occur when different D&I provide contradictory information about the same aspect, leading to ambiguity. A comprehensive delineation of uncertainties is omitted here, with reference directed to the explanations provided in (Gadzo et al., 2024).

4. State of the art

In the field of ontology research, numerous studies have engaged in literature reviews focused on ontologies. These efforts are often motivated by task- or domain-specific objectives, as exemplified by studies from Qaswar et al. (2023) and Yang et al. (2019), or works such as that of Karabulut et al. (2024), which illuminate ontologies in the context of digital twins. The presentation and analysis of results vary from categorizing literature sources by domains to engineering-oriented examinations of the ontologies themselves. This paper concentrates on identifying and analyzing existing ontologies in the domain of satellite development. To this end, the literature sources were categorized into the seven thematic areas introduced in Section 2. Within the scope of this paper, only a reduced portion of the research results is elaborated upon, as a comprehensive presentation would exceed the frame of this paper. The following discussion focuses solely on the state of the art in relation to the development of space objects and systems engineering, along with the associated modeling languages of MBSE, as these serve as a foundation and source of inspiration for the development of the ontological concept.

Zhao et al. (2020) present an ontological system that encapsulates satellite domain knowledge, as well as a method for accessing knowledge to execute task plans. This is accompanied by an architecture for configuring satellite clusters based on derived knowledge. Halvorson et al. (2022) present an ontology for prognostic health management in spacecraft avionics. Their work offers insights into the history of ontology, concept definitions, and elucidates the use of the Space Object Ontology (SOO) by Alexander P. Cox et al. (2016) in characterizing relationships between various spacecraft components and their functions. Given the relevance of SOO to this work, the results of Halvorson's study are pertinent. Further elaboration on SOO follows in section 5. Furthermore, Hening et al. (2016) describe the development and application of an ontology for space system design, serving as an OWL 2 (Ontology Web Language) complement to existing system databases. They advocate for a combined use of SysML and OWL models, with the former employed for model-based systems engineering and the latter for enhancing semantic precision in the application of operational knowledge. Huang et al. (2023) provide an illustrative example of a domain-specific ontology developed using the Ontology 101 method by Noy & McGuiness (2001), aimed at recommending virtual constellations in remote sensing. Methods for ontology development are discussed in more detail in Section 5. (van Ruijven, 2015) presents an ontology for systems engineering as a foundation for MBSE, utilizing so-called RDF-named graphs to integrate individual sub-models into a cohesive ontology. RDF (Resource Description Framework), based on subject-predicate-object triples that resemble simple sentences in natural language, is extensively explained in van Ruijven's contribution. Another relevant ontology, which is further discussed in section 5, is the MBSE ontology by Holt & Perry (2019) . The authors aim to provide a comprehensive and practice-oriented guide for the successful implementation of MBSE using SysML. They offer practical instructions for applying SysML in MBSE projects on one hand, and address advanced concepts for requirements management, architecture modeling, and competency management on the other. The MBSE ontology described therein is an integral part of the framework, which represents one of the three key elements of the presented MBSE approach.

Finally, the contributions of Cranefield & Purvis (1999), Wang et al. (2001), and Iribarne et al. (2011) are noteworthy for their focus on the use of UML in ontology modeling. Cranefield & Purvis (1999) explore the potential of object-oriented standards for ontology modeling, particularly UML and the associated OCL (Object Constraint Language), presenting a formalism for ontology representation as a UML subset in conjunction with OCL. Wang et al. (2001) propose a modeling approach for ontologies in UML that facilitates the mapping of knowledge to software models.

5. Preliminary study

Regarding the first preliminary question, it can be observed that while ontologies exist for the domain of space objects, they are not explicitly designed to support the task of identifying uncertainties in data and information, as well as their flows in the development process of a satellite project. The objective for the ontology approach is derived from this task and demonstrates the necessity to develop a domain-specific ontology with a corresponding focus. Although no ontology directly addresses this subject matter, existing ontologies have been identified that can serve as a foundation for developing a targeted ontology. In this context, it is essential to define goals (G) that this foundation should fulfill. Against this background, the following objectives were formulated and documented in Figure 3.

Goal	The ontology should…
G1	provide relevant concepts and relationships from the domain of space objects.
G2	be based on a top-level ontology to promote reusability and avoid isolated solutions.
G3	provide concepts and relationships aligned with the SysML meta-model, as it will be created in SysML and utilized in the context of SysML models.
G4	provide relevant concepts and relationships from the fields of systems engineering and model-based systems engineering.
G5	introduce a concept for using ontologies and element libraries to support effective modeling and ensure consistency between modeling elements and the ontology.

Figure 3. Goals for development fundamentals

As a result, four ontologies have been identified that collectively fulfill the determined goals. **The Space Object Ontology (SOO)** by Alexander P. Cox et al. (2016) is the first ontology identified as a foundation, as it fulfills G-1 and G-2. The SOO was developed to improve the characterization of space objects, integrate diverse datasets from various sources within an extensible framework, and facilitate entity tracking (G-1). The SOO is based on the Basic Formal Ontology (BFO) at the upper level and the Common Core Ontologies (CCO) at the middle level, thus extending a top-level ontology (G-2). It comprises over 700 classes representing diverse space entities, from natural and artificial resident space objects (RSOs) to spacecraft components and spatial regions. The SOO provides a standardized annotation language, enabling comprehensive representation of space objects, their processes, environments, and interactions. Furthermore, the SOO offers the necessary flexibility for extensions and adaptations to meet specific task requirements. This ontology will be utilized as a fundamental resource for domain-specific aspects in the ontology development process. In the course of investigating the state of the art, two ontologies were identified that can fulfill goals G-3 and G-4: the MBSE ontology by Holt & Perry (2019) and the Systems Engineering ontology by van Ruijven (2012a, 2012b, 2015). Van Ruijven's ontology is based on ISO 15926-11 and encompasses various information models for defining stakeholder requirements, system requirements analysis, operation and maintenance, verification processes, and risk management (G-4). The MBSE ontology, on the other hand, aims to represent system concepts and relationships in a standardized and formal manner. This is intended to enable consistent communication and a unified understanding between engineers and stakeholders, serving as a domain-specific language for MBSE activities (G-4). According to Holt & Perry (2019), the MBSE ontology is essential for MBSE endeavors and is applied in various activities, such as defining concepts and terms. It serves as a starting point for creating and adapting ontologies for individual MBSE activities, thus supporting the goal of integrating aspects from multiple ontologies. As both ontologies were specifically developed for MBSE, they are fundamentally compatible with the SysML meta-model (G-3). Extensions and adaptations can be realized through mechanisms such as stereotypes and profiles to represent specific requirements or areas not directly covered by standard SysML elements and relationships. For further work, the **MBSE ontology** is preferred, as it is comprehensively defined and explained in (Holt & Perry, 2019), thus providing valuable guidance in developing an application-specific ontology. To address G-5, (Borst et al., 1997) and the cross-domain ontology **PhysSys** described therein were identified as a source of inspiration. PhysSys forms the foundation for OLMECO, a library of reusable technical model components for simulating physical systems. The PhysSys ontology describes the composition of models from components of the OLMECO library. This interaction with the element library promotes the reuse of model components and increases efficiency in modeling, thereby fulfilling G-5. To address the second preliminary question, the works of Fernández-López & Gómez-Pérez (2002), Gomez-Perez et al. (2003), and Jones et al. (2007) were consulted, each containing a description and summary of methods for ontology development. The following seven criteria were defined to evaluate the identified methods for ontology development. Results are presented in Figure 4:

- C1: Existing ontologies should be considered
- C2: The method should be suitable for novices in ontology development
- C3: The method should not have a language dependency
- C4: The method should consider the use of element libraries
- C5: The method should be structured in a comprehensible manner
- C6: The focus should not only be on extending or enhancing an existing ontology

	U&K	KACTUS	SENSUS	METHONTOLOGY	TOVE	CYC	Ahmed
C1	✓	✓	✓	✓	✓	✗	✓
C2	✓	Limited	✓	✓	✗	✗	✓
C3	✓	only on initial ontologies	✓	✓	✓	✗	✓
C4	✓	Conditioned by initial ontologies	✓	✓	✓	✗	✓
C5	✓	✓	✓	✓	✓	✓	✓
C6	✓	Merging and extending	✗	✓	✓	✓	✓

Figure 4. Evaluation of the methods

To maintain the scope of the paper, the following presents just a concise summary of the evaluation results, considering the findings in figure 4: Novices in ontology development should initially apply *METHONTOLOGY* or the *U&K method* of Uschold & King (1995) to achieve positive outcomes. Experienced developers can significantly accelerate development using the *KACTUS* approach; however, expertise is required to implement adaptations professionally. Therefore, we will primarily utilize *METHONTOLOGY* and the *U&K method* as methodological guidance for developing an ontological concept. Further information on these methods can be found in the aforementioned sources.

6. The ontological concept

Before presenting the structure of the ontological concept we briefly address its role within the framework of the methodology. The methodology currently under development consists of four building blocks. The first is a procedural model that, among other things, describes the fundamental role of system modeling in solving the task at hand. A detailed description of this process model can be found in (Gadzo et al., 2024). The second building block is a method collection that provides descriptions of how models can be created using the SysML language for specific analytical purposes. Further information on these methods is contained in (Gadzo et al., 2023). The third component is an element library containing standardized modeling elements available to the modeler during model construction. Finally, based on the ideas of Borst et al. (1997) and the PhySys ontology, this approach serves both as the foundation for the element library and as a structured knowledge representation. Figure 5 visually summarizes the different roles of these building blocks.

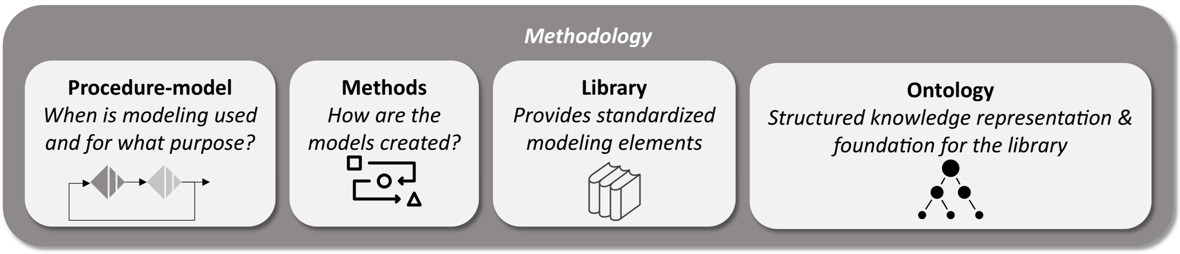

Figure 5. Overview of the methodological components

The concept's modular structure, developed using the Systems Modeling Language (SysML), comprises three main components, as illustrated in Figure 8: the General Ontology, the Structure Ontology, and the Uncertainty Ontology, complemented by the Element Library. The General Ontology (Figure 6) serves as the central element, providing a formal specification of concepts and their relationships for analyzing uncertainties in document-based data and information. It contributes to the reduction of inconsistencies, inaccuracies, discrepancies and ambiguities, and helps to mitigate them in model creation through clear definition of requirements satisfaction, precise specification of architectures, and explicit representation of system contexts. Inspired by the MBSE ontology of Holt & Perry (2019) the General Ontology presents a novel ontological approach, divided into the sections of requirements, behavior, and system of interest, with *function* acting as the central linking element. The color differentiation within the sections illustrates the hierarchical levels of the ontology. A crucial technical aspect is the definition of multiplicities, which specify the interactions between concepts in a precise way. For example (see Figure 6), a *functional requirement* shall be *satisfied by* at least one *function (1),* while multiple *functions (1..*)* can *be realized by* the *System of Interest (1)*. This *System of Interest (1)* is represented by *functional, logical, and physical architectures (1)* and interacts within one or more defined *System Contexts (1..*)*. This precise specification contributes to the development of meaningful analytical models. When combined with the methodology's analytical methods and procedural model, this creates a comprehensive framework that guides modelers in creating models for the task at hand.

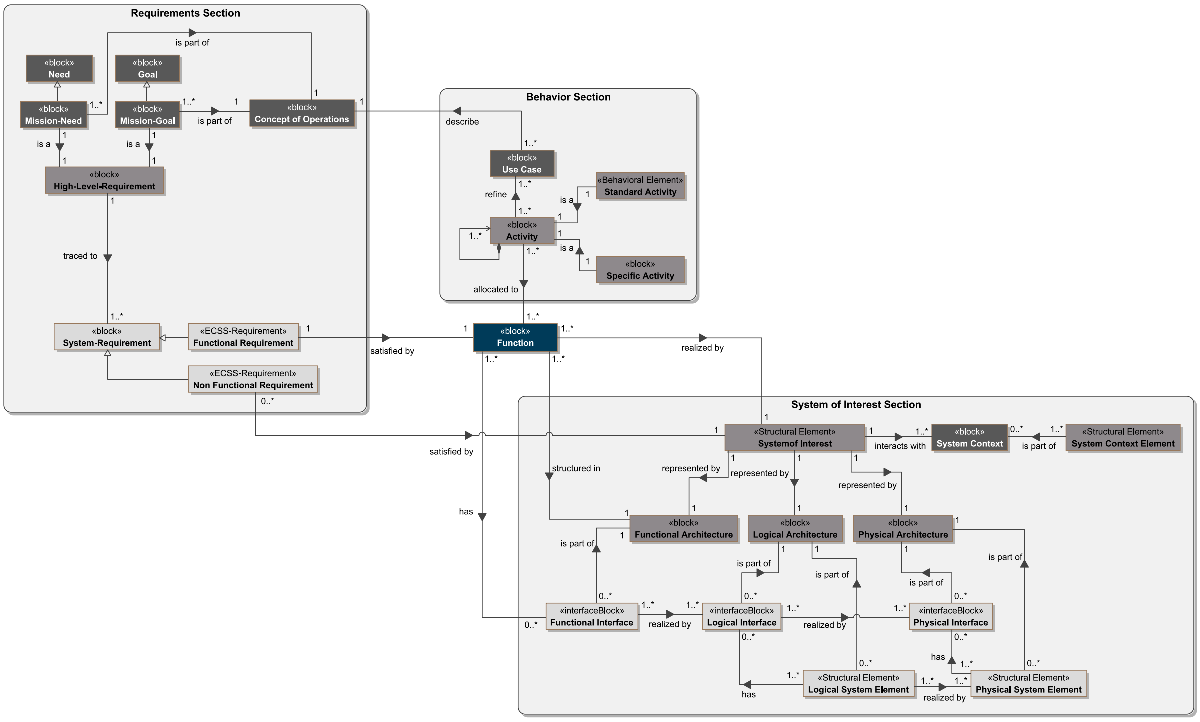

Figure 6. The General Ontology

As part of the ontological concept, the Structure Ontology extends the General Ontology with domain-specific components and information, creating a flexible tool for model creation applicable to both subsystems of the satellite system and the entire space segment. Each element is equipped with relevant attributes representing properties significant for analysis, with concrete values defined project-specifically and maintained in the element library. The development of the Structure Ontology followed the METHONTOLOGY guideline through an iterative process involving domain experts for reviews of the artefacts, according to a support evaluation in the Design Research Methodology (DRM) of Blessing & Chakrabarti (2009, p. 176-177). An analogous methodological approach was applied to the general ontology, though with reduced scope. The SOO by Alexander P. Cox et al. (2016) served as a foundational reference for the Structure Ontology. Figure 7 shows a small section of the domain specific Structure Ontology and, for this purpose, contains only the top-level concepts and relationships. The ontology, however, extends down to the component level of satellite projects. Since this ontology is very extensive, a holistic representation is not possible within the scope of this article.

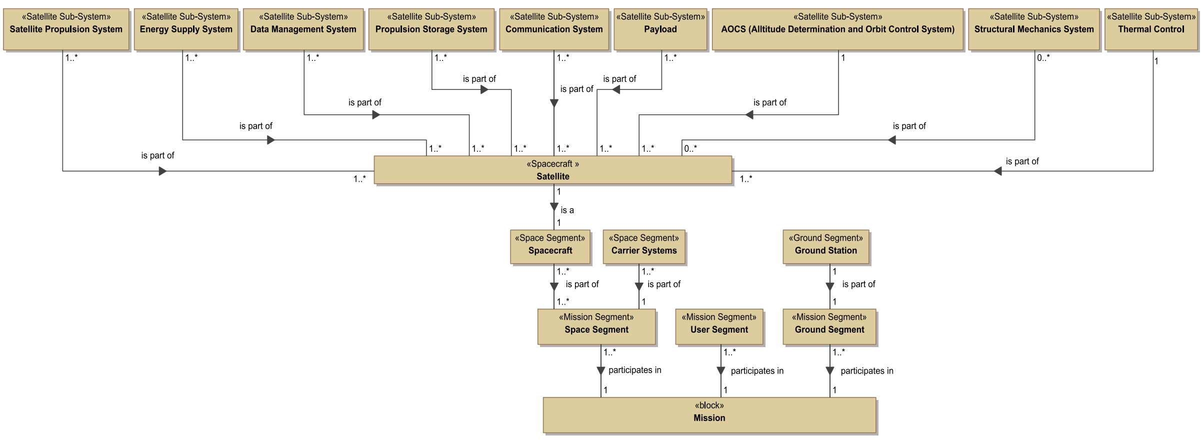

Figure 7. Top levels of the structure ontology

The Element Library contains all concepts defined in the Structure Ontology and provides modelers with relevant domain-specific elements. Information about their relationships is available through the ontologies. The Structure Ontology thus contributes significantly to the identification and mitigation of uncertainties, as the modeler can recognize incomplete information during model construction. This transforms unknown unknowns into defined known unknowns. The Uncertainty Ontology enables these identified uncertainties to be categorized and considered in the further development process. The visualization of the Uncertainty Ontology in Figure 8 illustrates the various categories of uncertainties considered within the methodology. Both the General Ontology and the other ontologies are fundamentally expandable and can be refined independently of each other, underscoring the flexibility and adaptability of the entire concept. The modular structure provides a defined separation between domain information and the relationships relevant for analysis, which fundamentally enables a broad domain-independent application of the concept. This only requires the development and provision of an appropriate Structure Ontology for the domain under consideration. The application and success validation of the ontological concept is carried out within the framework of the methodology validation. The DRM of Blessing & Chakrabarti (2009) builds the methodological frame for the initial validation, as part of the descriptive study II phase of the development of the methodology. For this purpose, a subsystem of the SeRANIS small satellite project, as described by Kinzel et al. (2022), is utilized. It's existing document-based data and information will be analyzed for the uncertainties defined in the Uncertainty Ontology. The aim is twofold: firstly, to demonstrate the applicability and effectiveness of the methodology, and secondly, to reduce the entry barrier and promote the acceptance of MBSE in development projects through this targeted, task-specific application of MBSE. The validation will include collaboration with systems engineering engineers and domain-specific developers, thus providing broad insights into the applicability and success of the development support.

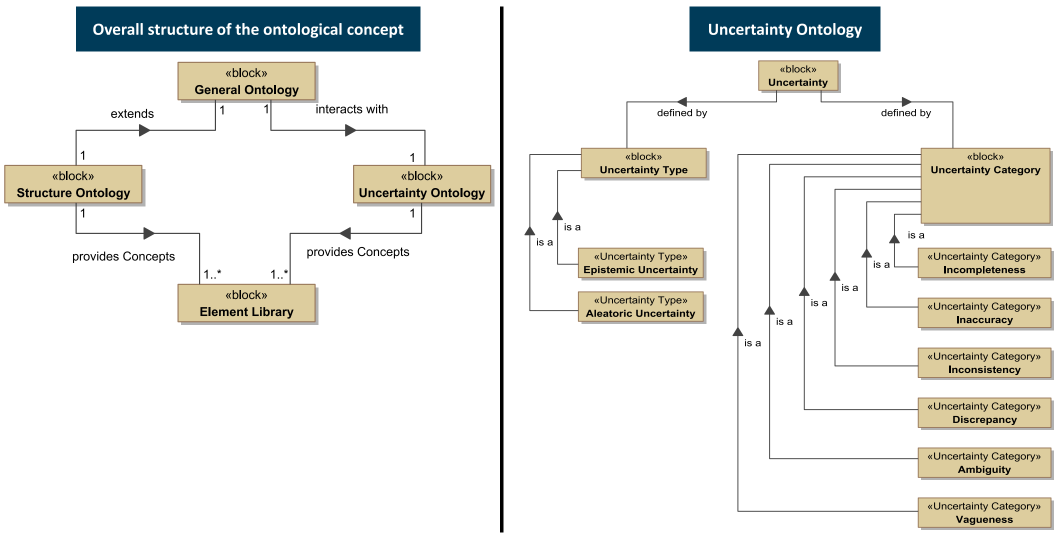

Figure 8. Overall structure of the ontological concept & the Uncertainty Ontology

7. Summary and outlook

This paper introduces an ontological concept, developed using the SysML, aimed at facilitating the identification and mitigation of uncertainties in data and information within a methodology framework for model-based support of satellite development projects. The work outlines the results of preceding preliminary studies, which form the foundation for the development of this ontological concept. The proposed approach encompasses an overarching ontology, the *General Ontology* which contains the concepts and relationships relevant to the methodology and its associated analytical methods. Furthermore, two sub-ontologies are introduced: the *Uncertainty Ontology* which describes the concepts of the uncertainties under consideration, and the *Structure Ontology* which comprises a comprehensive collection of domain-specific concepts and their relationships. Future work will focus on refining the *General Ontology* and further refinement of the *Structure Ontology* through the specification of attributes for the concepts and the development of the element library. The next critical phase involves validating the approach and incorporating insights derived from the validation of the presented concept.

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