Metaization concepts for monitoring-related information

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Abstract

In recent years, structural health monitoring (SHM) has become a widely used state-of-the-art method for analyzing and assessing the condition of civil infrastructure. SHM systems are characterized by a plethora of heterogeneous system components. For optimizing, documenting, and change tracking of SHM systems, information about SHM systems needs to be formally described on a sound basis. However, with current methods, such as ontologies, description languages or metamodels, only a small subset of information inherent to SHM systems, such as information about sensors, can formally be described. This paper presents a conceptual approach towards identifying and specifying monitoring-related information. Based on a summary review of SHM modeling approaches, metaization concepts to overcome the current limitations are discussed and a robust formalism to describe SHM systems mathematically is proposed. The review methodology is based on a three-pillar concept. First, regulations, standards, and guidelines related to SHM and, second, the current research landscape is examined to identify information required for describing SHM systems, and hierarchies of terms are proposed to categorize the findings. Third, metamodel architectures, such as SHM-related ontologies, BIM-based metamodels and description languages, are reviewed with respect to formally describe SHM systems. Being part of the third pillar, mathematical metamodeling approaches based on category theory, set theory and type theory are presented, capable to describe SHM system as well as approaches suitable to couple metamodels. As an outcome of this study, besides a comprehensive review of the above directions, a strategy towards developing a metaization concept is proposed to
provide a robust formalism for SHM system descriptions, aiming to advance optimization, documentation, and change tracking of SHM systems.

**Keywords:** Structural Health Monitoring, Building Information Modeling, Metamodeling, Semantic Modeling.

### 1. Introduction

Emerging sensing technologies, facilitating data acquisition, data analysis, and data exchange in structural health monitoring (SHM), have been gaining increasing interest in civil engineering [1]. Data formats used to describe SHM systems as well as civil infrastructure being monitored have been defined to advance high-quality digital processes in all phases of the life cycle of civil infrastructure [2, 3]. Traditional building information, such as geometry, material and cost, falls within the scope of “building information modeling” (BIM) and has been a subject of research and industrial development since many years [4]. By contrast, information about SHM systems, referred to as “monitoring-related information”, cannot be fully described on a well-defined, formal basis [5]. Monitoring-related information, such as information about the semantic composition of SHM systems, about embedded algorithms implemented into sensor nodes, or about locations and specifications of sensors, can advantageously be used for SHM system optimization and documentation. Because of insufficient modeling and metamodeling concepts for SHM systems, optimization of SHM systems during the design phase of structures, consistent digital archiving of monitoring-related information, and accurate, quantitative assessment of structural condition is often not supported by today’s modeling and metamodeling concepts.

In the life cycle of SHM systems, a variety of parties are involved in the life-cycle phases of SHM systems. In the pre-design phase, structural designers develop drafts of structural elements, while interacting with specialist designers of SHM systems who define structural conditions to be monitored. In the design phase, monitoring approaches are defined and reviewed with respect to feasibility
aspects by engineers installing SMH systems. Upon identifying the “best” monitoring approach, installation methods are developed and coordinated with general contractors who are responsible for documenting the installation. For initial monitoring, the contractors are in contact with operators managing SHM systems during the operation and maintenance phase. Operators are responsible for providing sensor data to be analyzed by structural engineers for structural assessment and for providing recommendations with respect to further operation. Accurate descriptions of SHM systems in association with the structures being monitored enhance planning and documentation activities over all phases of the life cycle.

With recent technological advancements, civil infrastructure is equipped with intelligent sensor nodes, enabling automated SHM [6]. Spatially distributed in infrastructure systems and communicating with each other, intelligent sensor nodes autonomously collect sensor data, process sensor data, and assess infrastructure conditions in real time. In addition, integrating engineering models into sensor nodes, both data-driven and physics-based models, advances digital descriptions of civil infrastructure in a fully decentralized manner [7]. With model integration into sensor nodes, a new multi-paradigm approach evolves, combining monitoring-based and model-based structural assessment methods. However, precisely evaluating the quality of models for structural assessments is hardly possible using state-of-the-art methods [8]. Thus, metaization concepts are required to provide a sound basis for developing novel structural assessment methods, entailing general metamodel architectures for SHM systems.

Metamodels specify abstract syntaxes to describe models in distinct model domains, essentially providing methodologies to represent information that characterizes models. While metamodel-based approaches have been a subject of research in computer science, in systems engineering, and in business management since decades [9], concepts of metamodeling have been applied in civil engineering over the last few years [8]. Following the increasing digitalization efforts in the architecture, engineering, and construction (AEC) industry, metamodel architectures may contribute to
developing modeling concepts for engineering systems and, in particular, to integrating engineering models in the context of SHM.

Providing well-defined formalisms, metamodel architectures facilitate life-cycle oriented documentations and methods to continuously update monitoring-related information. Therewith, it is expected that the quality of SHM systems and the quality of models for structural assessment can substantially be enhanced. Providing a basis for developing metaization concepts, this paper focuses on formalisms to semantically describe monitoring-related information. Monitoring-related information is heterogeneous and partly unstructured, since sources of information are stemming from different domains or are even of cross-domain nature. Therefore, this paper summarizes sources of information, following a methodology towards developing a metamodel approach to systematically identify monitoring-related information. In summary, developing a metamodel approach for describing and managing SHM systems entails distinct advantages, such as:

1. Generating digital models for SHM systems and structures being monitored
2. Effective planning of SHM systems
3. Improving data control and management in the operation and maintenance phase
4. Linking SHM system components with monitoring and simulation data
5. Integrating 3D and 4D visualization of sensors and sensor data
6. Sorting, scheduling, and querying monitoring-related information
7. Easy integration of monitoring-related information into models used for structural assessment

This paper is organized as follows. First, the methodology of the summary review is presented. Then, SHM-related regulations, standards, and guidelines relevant to describing monitoring-related information are discussed and monitoring-related information to be described is identified. Next, monitoring-related information from recent research not covered by existing regulations, standards, and guidelines is summarized. Then, metamodel architectures enabling the description of monitoring-related information are presented and examined with respect to their suitability of describing SHM
systems on a formal basis. Thereupon, mathematical approaches and approaches coupling different metamodels are presented. The paper concludes with a discussion of the results of the summary review and with a proposal for further research approaches towards semantically describing SHM systems.

2. Methodology to develop metaization concepts for monitoring-related information

The quality of SHM systems applied to civil infrastructure depends on the quality of monitoring-related information, such as information about the hardware used for data acquisition (e.g. sensors), about equipment used for data transfer (e.g. wireless transceivers), or about models utilized for SHM (e.g. physics-based or data-driven models). To quantify the quality of SHM, monitoring-related information needs to be consistently described on a formal basis. Therefore, a systematic conceptual approach towards identifying and specifying monitoring-related information is presented in this paper. Specifically, a three-pillar concept (Figure 1) is shown, aiming at semantically describing SHM systems:

1. Existing regulations, standards, and guidelines directly or indirectly related to SHM are summarized. Monitoring-related information to be described is extracted, hierarchically structured, and aggregated into a hierarchy of terms (Section 3).

2. Information about SHM systems from recent research not covered by the formalized approaches of the first pillar, such as information about the inherent and dynamic logics of sensor nodes in wireless SHM systems, is analyzed, described and also aggregated into a hierarchy of terms (Section 4).

3. First, metamodel architectures are evaluated with respect to suitability of describing monitoring-related information. Then, ontologies and description languages related to SHM or, in particular, to sensors and sensor networks are analyzed. Next, approaches describing SHM systems within the scope of BIM (using BIM data formats as metamodel architecture) and on a mathematical basis are considered. Finally, approaches are presented towards coupling metamodels for describing monitoring-related information (Section 5).
As a result of the summary review, descriptive capabilities are deduced based on the three-pillar concept, to be reused for describing monitoring-related information (Section 6), i.e. information that has been available only in an unstructured and heterogeneous form, is now available as a hierarchy of terms. Metamodeling concepts may contribute to increase the quality of formally describing monitoring-related information. In future work, the modeling concepts evaluated in this paper may be transferred into a metamodel to describe monitoring-related information. In association with BIM-based metamodels widely used in civil engineering, a complete description of civil infrastructure including SHM systems may be advanced. Potential future work is discussed in Section 6.

Figure 1: Towards metaization concepts for monitoring-related information.

In the following section, an overview of sources of monitoring-related information is presented, summarizing monitoring-related information identified from SHM-related regulations, standards, and guidelines. The summary provides a basis for describing information about SHM systems, aiming to support developing metaization concepts for monitoring-related information.
3. SHM-related regulations, standards, and guidelines

Sources of monitoring-related information are distributed over a plethora of SHM domains. This section summarizes monitoring-related information from regulations, standards, and guidelines. The objective is to hierarchically structure and aggregate the monitoring-related information into a hierarchy of terms that may serve as a basis for developing metaization concepts for monitoring-related information.

One of the first SHM guidelines have been the “guidelines for structural health monitoring” proposed by Mufti [10], as introduced by the Structural Innovation and Monitoring Technologies Resource Centre, Canada. The guidelines illustrate advantages of deploying SHM systems and divide SHM systems into six components: Data acquisition, data communication, data processing, data storage, diagnosis, and data retrieval. In the guidelines, the “testing” applied by SHM systems, i.e. how data is physically collected, is prescribed to be documented according to static field testing, dynamic field testing, periodic monitoring, and continuous monitoring. As described in the guidelines, the sophistication level of SHM systems increases according to the monitoring objective, which should therefore be documented as damage detection, damage location, damage quantification, and consequences of damage (safety evaluation).

Regarding data acquisition, the guideline F08b published 2006 by Rücker (“Guideline for structural health monitoring”) prescribes the documentation of (i) monitoring patterns to be used (i.e. continuous, cyclic, event or load-dependent), (ii) monitoring strategies (i.e. global or local strategy), and (iii) monitoring instrumentation (e.g. sensor types, sensor protections) [11]. In terms of structural diagnoses, methods used for damage identification (e.g. frequency responses or threshold values) and common damage causes (e.g. corrosion and cracks) are prescribed to be documented. Moreover, sensor embedment (placement of sensors in structure surfaces or inside materials), measuring patterns, and environmental protection are important issues to be addressed. In the guideline (“Bridge
monitoring”) of the German Concrete and Construction Technology Association (DBV), instructions for monitoring bridges and other structures during their lifecycle are prescribed [12]. In particular, the objective, the monitoring concept, and the monitoring tasks must be documented. In addition, measurands, measuring methods, locations of equipment, measuring durations, data processing, and cost estimations must be described. Furthermore, sensor installations and calibrations, energy supply, data management, and evaluations of results are to be reported.

In a technical report of the United States Department of Transportation (“Development of a model health monitoring guide for major bridges”), SHM is introduced for owners, engineers, operators, and managers of bridges [13]. According to the technical report, technologies to perform SHM must be documented and classified as analytical technologies, experimental technologies, and information-related technologies. Analytical technologies involve linear and non-linear analyses, experimental technologies include data measuring and structural testing, and information-related technologies contain data acquisition and communication systems. In addition, data acquisition systems, network communication and control, measurement calibration, data management, and data interpretation must be documented. In another report of the United States Department of Transportation, FHWA-HRT-09-040 (“State of the practice and art for structural health monitoring of bridge substructures”), further guidelines regarding documentation are given, e.g. about documentation of sensor location, sensor type, data recorded, and analysis results [14]. In addition, the documentation of SHM systems contains on-site equipment, personnel qualifications for inspections, construction methodology of the structure, and results from inspections classified according to structural components as described in the protocols of the United States Department of Transportation, FHWA-HRT-16-007 (“Long-term bridge performance (LTBP) program protocols, version 1”) [15]. The protocols aim at collecting exhaustive data from bridges, facilitating time-variant comparative analyses across structures.

In a report of the Structural Engineering Institute of the American Society of Civil Engineers (ASCE) entitled “Structural identification of constructed systems”, monitoring systems are considered connective links aiming at closing gaps between numerical models and real systems [16]. The report
differentiates six steps in structural monitoring: Conceptualization, modeling, experimentation, data processing, modeling calibration, and decision making. In the experimentation step, experiment classifications, sensor classifications, data transmissions, data acquisitions, and non-destructive methods utilized must be documented. During the data processing step, the interpretation type and algorithms must be archived. In the modeling calibration step, engineering models must be recorded along with the model calibration techniques, and in the decision-making step, the performance limit state is to be defined and documented.

Besides information about the SHM system, the structure type must be documented and classified according to high-rise buildings, long-span spatial structures, bridge structures, and others, as described in the Chinese standard GB 50982-2014 (“Technical code for monitoring of building and bridge structures”) that has been published by the Chinese Ministry of Transportation in 2014 [17]. The standard covers a major part of monitoring methods currently applied in China, enforcing sensor installation on buildings and bridges. Depending on the structure type, general requirements, construction and post-construction monitoring guidelines are given. Moreover, documentation of sensors requirements (e.g. durability and maintenance), documentation of data requirements (collection, transmission, processing, and management), and documentation of safety evaluation requirements (i.e. safety evaluation according to structural states) must be considered.

Aiming to timely identify and evaluate defects and damage, the German standard DIN 1076:1999-11 (“Engineering structures in connection with roads – Inspection and test”) defines basic regulations for inspecting and monitoring civil engineering structures in the course of roads with regard to stability, safety, and durability [18]. In general, maintenance plans and responsibilities for monitoring must be clearly documented. More precisely, the actions executed and the time of execution as well as documentation obligations for inspections and for monitoring systems must be described. In the guideline RÜV:2008 (“Guideline for monitoring of road safety of federal structures”) of the German Federal Ministry of Transport, Building and Urban Development (BMVBS) additional documentation obligations are described [19]. According to this guideline, responsibilities and competences must be
clearly regulated and documented. In addition, information on findings, type, scope, and frequency of monitoring processes, and on actions required to avert and remedy damages, must be documented.

Prescribing general documentation obligations, the Austrian Research Association for Roads, Railways and Transport (FSV), in regulation RVS 13.03.01:2012 (“Monitoring of bridges and other civil engineering structure”), describes requirements for structural health monitoring of bridges and of other civil engineering structures in the course of roads [20]. The regulation prescribes the documentation of schedules for monitoring purposes and of requirements regarding the personnel needed for conducting the monitoring processes. In addition, the documentation must contain assessments regarding conditions of structures and results of structures monitored. The assessments are crucial for management of maintenance and, thus, allow optimizing maintenance plans and expenditure. Focusing on inspection and maintenance, the standard BD 63/17 (“Highway structures: Inspection and maintenance Part 4”) of the United Kingdom regulates documentation obligations, such as inspection date, responsible person for inspections, general information regarding the structure, and weather conditions during inspections are mandatory to be documented [21]. Moreover, identification of structural parts and inspection intervals must be documented as well.

For assessing the structural health of dams, individually designed SHM and control systems are essential. Therefore, static, hydraulic, hydrological, and operational conditions and loads must be continuously recorded by SHM systems. The German Association for Water, Wastewater and Waste (DWA) has published a guideline on dam monitoring, DWA-M 514:2011 (“Dam Surveillance”), ensuring the reliability of dams in all phases of construction and operation [22]. The guideline prescribes documentation of information about measuring methods and measuring systems for monitoring quantities and measurands influencing the structural condition of civil infrastructure. In addition, SHM systems must be designed within the planning phase of new dams; specifications of maintenance and inspections of SHM systems must be documented in advance. Once methods for achieving monitoring objectives are determined, considering operational and extreme conditions, measurement methods must be developed that can reliably monitor quantities and measurands. For
automated methods, algorithms for calculating measurands must be documented. Furthermore, information about monitoring objectives must be documented, describing accuracy specifications, measuring devices (e.g. instruction manuals for handling, calibration, and adjustment of the devices), results of measurements (e.g. calculation, documentation, and archiving of the results), frequency and timing of measurements, and expected as well as critical values for measurements.

Monitoring-related information, as a result of analyzing the SHM standards, regulations, and guidelines presented in this section, is summarized in the following paragraphs. The information from the above sources is hierarchically structured and aggregated into a hierarchy of terms to characterize SHM systems. As shown in Figure 2, the hierarchy of terms distinguishes between information associated with seven categories: Data acquisition, data communication, data processing, data storage, data interpretation (diagnosis), data retrieval, and general information.

- The **data acquisition** category documents information describing (i) monitoring patterns, (ii) sensors, and (iii) measuring methods. Monitoring patterns characterize time and duration measurements are performed. Sensors, which may be covered by protective devices, have a location (e.g. geodetical coordinates) and a number of technical properties describing a sensor in more detail. Depending on the sensor, a measurand characterizes the sensor output. Within the scope of data acquisition, manuals for installation, handling, calibration, adjustment, and replacement of technical devices must be provided. Installation histories associated with sensors enable tracking replacements during the life cycle of monitoring systems. In addition, documenting costs of sensors is important in the planning phase of SHM systems as well as in the operation and maintenance phase. Finally, the measuring methods contain, for example, descriptions of the general method applied and information about measurands.

- For documenting **data communication**, the communication units of SHM systems and the network topology of the communication units need to be described. Depending on whether wireless or tethered technology is used, data communication protocols and protocol-specific
information are to be documented. Furthermore, the range of the communication units must be part of the documentation, in particular if wireless technology is used.

- Related to **data processing**, information about processing devices of SHM systems and analytical technologies applied to the devices need to be documented. Inputs and outputs, such as measured and observed values as well as accuracy aspects, need to be described clearly. In addition, the processing steps, i.e. the algorithms applied to the input data to calculate the output data, must be documented.

- Information about **data storage** describes storage devices containing information about types, locations (physical addresses), memory sizes and speeds of the devices. Also, details on storage, e.g. locations (memory addresses), timestamps, units, or data formats are to be documented. Further information related to data management, such as the frequency used for storing data, must be described.

- For **data interpretation (diagnosis)**, the diagnostic devices of SHM systems and the algorithms used to interpret data are to be documented. For comparing sensor data with data from engineering models, e.g. numerical models or experimental models, the engineering models must be available to actors in the remaining lifecycle of SHM systems.

- The category **data retrieval** includes information about devices used for retrieval purposes or for controlling structures, e.g. by actuators. Therefore, information about the devices as well as the algorithms executed on the devices must be documented. Furthermore, the findings of former data interpretations must be stored and archived.

- Information generally related to SHM systems that cannot be associated with one of the six categories described in the previous paragraphs is collected in the **general** category. The general category contains information about (i) life times of SHM systems, (ii) objectives of SHM systems including overall monitoring strategies and scopes, (iii) maintenance aspects, (iv) actors, i.e. persons and organizations, involved into SHM projects, and (v) structures to be monitored.
In this section, monitoring-related information identified from SHM-related research not covered by regulations, standards, and guidelines is summarized and aggregated into a hierarchy of terms of SHM-related research to further characterize SHM systems.

Smarzly & Tauscher [5] have identified monitoring-related information crucial for describing intelligent SHM systems. A conceptual approach towards monitoring information modeling in civil engineering is presented. Monitoring-related information is distinguished between global monitoring-related information and local monitoring-related information. Global monitoring-related information, such as configuration and topology of sensor networks, interaction protocols, or monitoring strategies implemented, is typically assigned to whole SHM systems (or subsystems of SHM systems) and
cannot be assigned to specific devices of SHM systems. By contrast, local monitoring-related information, such as hardware specifications, types, and locations of devices of SHM systems (e.g. sensor nodes, sensors, actuators), algorithms embedded into sensor nodes for local processing of data, or inherent redundancies and correlations between sensors, is assigned to specific entities within SHM systems. Describing both global and local monitoring-related information enables consistent digital representations of all information relevant to intelligent SHM systems throughout the life cycle of civil infrastructure, thus substantially enhancing the monitoring quality.

In a subsequent paper, Smarsly et al. [23] focus on describing communication-related information as a subset of monitoring-related information including communication technologies, such as communication protocols and technical devices for coupling communication system components. A metamodel approach is presented to describe communication-related entities, properties of entities, and relations between entities. Communication-related entities, such as transmitters, receivers, transmission media, data units, electrical signals, information sources, and observations have been identified and categorized. In addition, aspects of autonomous devices, power consumption, and resource management (related to communication technologies) have been considered.

Aiming to improve cooperative management of structures and SHM systems, research endeavors conducted in the last decades focus on developing metamodels for describing monitoring-related information. Aruga & Yabuki [24] have developed a framework for cooperative decision-making in maintenance management of structures instrumented with SHM systems. A metamodel has been developed to describe monitoring-related information, such as information about changes of the (structural) state of structures or environmental conditions. With precise formulations of maintenance and inspection plans, safety, usability, and durability aspects have been considered. Monitoring of structures depends on the type of the structure and cannot be considered detached from the structure, as many factors depend on both the SHM system and the structural system. Therefore, it is important to model the SHM system in conjunction with the structural system. In the Ph.D. dissertation of Bai [25], a method for integrating of BIM-based technologies and radio frequency identification (RFID) is
presented, enabling automated structural condition assessment. To identify and locate cracks in structures, strain is measured with RFID-based wireless strain sensors. Therefore, it is crucial to exactly document measuring positions in BIM models. For prediction of future structural condition based on structural analyses, cracks must be documented within the scope of structural elements being monitored. Based on the history of structural condition stored in BIM models, the prediction quality can be increased.

Structure-related information in general and monitoring-related information in particular can be “static” or “dynamic”. The term “dynamic” refers to models not solely containing “static” information, such as design and construction data. Rather, information about building elements and SHM system components is updated with real-time information, e.g. based on sensor measurements. In the approach of Chen et al. [26], sensor data is connected with information of BIM models aiming to provide “dynamic” BIM models. With a “dynamic” BIM model, facility management can be improved, e.g. by faster reaction on emergencies, proactive maintenance planning, or identifying use patterns and trends. Therefore, in BIM models, elements being monitored and locations of sensing devices must be clearly documented. In addition, processes of documenting changes in structures or SHM systems must be clearly described.

BIM models may be used to store a plethora of information. However, if BIM models are continuously enriched with unstructured information, there is a risk that information will be described redundantly and contradictorily in the model. Proposed by Del Grosso et al. [27], an approach is presented progressively enriching BIM models of structures (equipped with SHM systems) with information becoming available during the life cycle of structures. Based on preliminary BIM models, information related to structures (and SHM systems) is added or updated to BIM models according to current levels of development of infrastructure projects. Thus, BIM models become more detailed in the course of planning, constructing, and operating of structures. Information related to monitoring is added, such as information about construction schedules, costs, facility management, and sustainability. The documentation of the information added or updated is essential in many life-cycle
stages to improve planning, constructing, and operating of structures that are instrumented with SHM systems.

Building information models should not only contain information on the current state of a building but also on the history. An approach towards life-cycle management of bridges is reported by Hammad [28]. Bridges, due to ageing of infrastructure increasingly instrumented with SHM systems, are complex structures containing a plethora of potential information. The quantity of bridge-related information is increasing during operation and enriched (or updated) by information on inventory, inspections, assessments of conditions and strengths, and decisions related to repair, strengthening, or replacement. In addition, data storage, cost and deterioration models, optimization models, analysis models, and updating functions must be clearly defined and documented. As a result, complete histories of structures (and SHM systems) become available at any time.

Information that is to be assigned to structural components should, if possible, be assigned to the components in the BIM model. However, the assignment must be clearly structured and tailored to the use case of the respective modeling. In the approach of Huston et al. [29], BIM models are used as a backbone of SHM systems. Monitoring-related information is categorized into six tasks and assigned to BIM objects: (i) Structural observations and measurements, (ii) information management, (iii) condition assessment, (iv) decision-making and planning, (v) implementation of repairs, and (vi) assessment of repair and maintenance performance. Accordingly, task-specific information is added to BIM models regarding, for example, sensor measurements, maintenance records, and repair reports.

An important part of modeling monitoring-related information concerns archiving of information on maintenance and inspections of SHM systems. A concept for model-oriented management systems is presented by Kubota [30], and a metamodel for maintenance systems in concrete highway bridges is proposed. The metamodel of maintenance systems contains information related to planning, inspections, deteriorations, soundness evaluations, repairs, and reinforcements. In addition,
maintenance plans, inspections plans, inspection data, deterioration judges, and repair data is collected in the management system.

As a result of analyzing SHM-related research, monitoring-related information from the above sources complementing the information stemming from SHM-related regulations, standards, and guidelines identified in Section 3, is hierarchically structured and aggregated into the hierarchy of terms to further characterize SHM systems. As shown in Figure 3, the hierarchy of terms distinguishes on the vertical axis between global and local monitoring-related information. On the horizontal axis, the hierarchy of terms distinguishes between monitoring-related information typically assigned to SHM systems and monitoring-related information typically assigned to structural systems. The hierarchy of terms may be used as a basis for developing a semantic model for SHM systems. Starting from information that is globally assigned to whole SHM systems, SHM systems can be semantically divided into computer systems and sensor networks. The computer systems are used to analyze monitoring-related information globally providing diagnoses and prognoses. Information from diagnoses and prognoses may influence maintenance activities. Sensor networks are aggregated into sensor nodes, base stations, and gateways. Sensor nodes can be further divided into sensors and actuators. On contrast, structural systems can be semantically divided into structural subsystems, such as building stories, or infrastructure sections. Structural subsystems can be further divided into structural elements, such as walls, slabs or pillars. For optimization of analyses of structural systems, the relationships between SHM system components (e.g. sensor networks or sensor nodes) and monitored structural components (e.g. structural subsystems or structural elements) have to be specified.
Figure 3: Hierarchy of terms, summarizing monitoring-related information identified from SHM-related research.

5. Metamodel architectures

Because monitoring-related information is inherently of cross-domain nature, the description of SHM systems is complex, containing information of different heterogeneous engineering fields. In general, two paradigms are facing each other when describing SHM system through monitoring-related information, (i) the description of SHM systems using a single (global) metamodel and (ii) the description of SHM systems using several domain-specific metamodels coupled with each other, typically referred to as “coupled partial models” or, more precisely, as “coupled partial metamodels”. In this paper, both paradigms are considered to identify promising approaches for developing metaization concepts for SHM systems.

The first paradigm (i.e., a global metamodel) aims to offer uniform formats for describing all monitoring-related information. However, global metamodels are limited if information out of the
scope of the metamodels is to be described. By contrast, the second paradigm (i.e., several domain-specific metamodels) is flexible because almost any type of metamodel may be used to describe domain-specific information. Therewith, the second paradigm is suitable to avoid the problem of out-of-scope information, however coping with other challenges, such as redundancy of information, the need for coupling mechanisms, and increasing implementation efforts that strongly depend on the number of partial metamodels used.

As shown in Figure 4, this section starts with an overview of general modeling languages, in the following referred to as “general meta-metamodels”, that can be used to describe both global and domain-specific metamodels. Then, SHM-related ontologies and description languages, BIM-based metamodels, and mathematical approaches are considered, examining the use of metamodels and approaches to describe monitoring-related information. Finally, coupling of metamodels is discussed.

![Metamodel architectures](image)

**Figure 4:** Metamodel architectures considered in this paper.

SHM-related ontologies and description languages are domain-specific metamodels in the field of SHM. In contrast, BIM-based models typically contain a plethora of information of structural systems and could therefore be categorized as global metamodels. However, monitoring-related information is partly out of scope of current BIM-based metamodels. Thus, research approaches are shown that
extend BIM-based metamodels to describe monitoring-related information. Furthermore, mathematical approaches can be used to improve both global and domain-specific metamodels.

5.1 General meta-metamodels

To describe models, modeling languages provide a basis to express entities as well as properties and behaviors of entities in specific domains. The methodology of describing information with models is also referred to as “model-driven development”. A realization of a model-driven development widely used in engineering is the Model-Driven Architecture (MDA) framework [31]. The MDA framework separates specifications of system functionalities from platform-specific implementations. To describe models in a platform-independent manner, so called “meta-metamodels” are used, serving as a model for a modeling language employed to describe metamodels containing entities with entity-specific properties and behavior.

The meta-metamodel Meta Object Facility (MOF) [32] provides a basis for defining and extending metamodels. Therefore, MOF uses object-oriented paradigms based on the Unified Modeling Language (UML) 2 infrastructure [33]. Reusing a subset of structural modeling symbols of UML 2, MOF is used to customize metamodels for metamodel-specific domains, so-called “profiles”. Profiles have been developed and standardized, for example, in the System Modeling Language (SysML) to describe systems and systems of systems [34], or in the Common Warehouse Metamodel (CWM) to describe warehouse and business intelligence metadata [35]. MOF-based modeling languages may be adapted to a wide range of applications in software engineering and system development. Thus, MOF-based modeling languages, in particular UML 2, are alternatives for describing monitoring-related information.

With UML 2, another profile based on MOF, any structural semantics and behavioral semantics of domain-specific information can be described. Thus, UML 2 can be applied to describe monitoring-related information, providing a wide variety of notations and modeling constructs to describe
components and behavior of SHM systems. By deriving MOF-compliant metamodels, UML 2 can be used to create profiles for different modeling purposes and domains, thus advancing the development of extensive metamodels of SHM systems.

With EXPRESS, another meta-metamodel provides capabilities to describe the structure of a metamodel. Originally proposed for describing automotive and mechanical design, EXPRESS is standardized in ISO 10303-11 [36] and has become a standard for describing product model data, in particular data as a basis of building information. By using a standardized meta-metamodel, metamodels may be defined containing standardized entities, which is exceptionally useful when information is exchanged between software applications.

5.2 SHM-related ontologies and description languages

Semantic modeling SHM systems is supported by ontologies and description languages created for describing sensors and sensor networks. Ontologies and description languages cover specific information to be described. In this subsection, ontologies and description languages are presented with strong emphasis on modeling capabilities.

The “Standard for a Smart Transducer Interface for Sensors and Actuators” published by the Institute of Electrical and Electronics Engineers (IEEE) is a standards family for a smart transducer interface for sensors and actuators [37]. The IEEE 1451 standards family, published over different years, is composed of seven volumes that describe enabling technologies and standardized interfaces for transducer connectivity to microprocessors, instrumentation systems and data acquisition, and control and field networks. The objective of the IEEE 1451 standards family is to develop a network-independent transducer interface to avoid errors due to manual configuration and to support a general model for transducer data, control, timing, configuration, and calibration. Each volume within the standards family describes different parameters of a general smart sensor model. The IEEE 1451.1 standard describes network-capable application processor information models for smart transducers,
described from a physical point of view (i.e. microprocessor and its supporting circuitry and hardware) and logical point of view (i.e. function blocks, components, and services), aiming at reducing the efforts of interfacing transducers to a network. Furthermore, the IEEE 1451.2 standard defines transducer electronic data sheets (TEDS), which describe transducer types, attributes, operation, and calibration, thus allowing an easy plug-and-play replacement of transducers. The other parts of the IEEE 1451 standards family define TEDS for specific purposes, e.g. digital communication, mixed communication, and wireless communication.

The Open Geospatial Consortium (OGC), as part of the Sensor Web Enablement (SWE) initiative, has published the second version of the **observations and measurements (O&M)** standard in 2013 [38] (Abstract Specification: Geographic information – Observations and measurements), which is also available as ISO19156:2011 (Geographic information – Observations and measurements). The O&M standard defines an abstract schema for observations and for inherent characteristics involved in making observations, i.e. relations between observations and objects under observations, properties of measurements, and observation procedures. Moreover, the standard is a system-independent, Internet-enabled methodology for data exchange between sensor network components and other systems. Conceptual schemas presented in the standard are proposed in accordance with UML, while the implementation is described in Extensible Markup Language (XML). The standard is limited to observations modeling.

The **SensorML** standard [39] (“OGC SensorML: Model and XML Encoding Standard”) is another part of the SWE initiative, which defines a sensor description language. The focus is put on modeling processes and processing components related to measurements and post-processing of measurements, including sensing units, transducer components, and computational processes. The SensorML concept enables interoperability for a better understanding and better information sharing of the processes executed by machines (and sensor systems, respectively). In SensorML, conceptual models are described using UML, and implementations are illustrated by means of XML, similar to the O&M standard. SensorML is a specialized process description language appropriate to sensor data
applications. Thus, every component modeled with SensorML is specified as a process, whether physical (e.g. detectors or actuators) or non-physical (e.g. mathematical operations or functions). The process model, defined in the SensorML standard, is an entity that, by means of precise methods and configurable parameters, produces one or more outputs from one or more inputs. Furthermore, SensorML supports additions and accumulations of processes, referred to as aggregate processes. Objectives of SensorML are to enhance inventory management by describing sensors and sensor systems, to support processing measurements, to geolocalize measurements, to explicitly describe recording of measurements, to provide aggregate process that can derive new data, and to archive properties and assumptions related to sensor systems. In addition, metadata is supported in SensorML, which is, however, not necessary for processes execution. Although sensor systems can be described with SensorML, it lacks capabilities to sufficiently describe specific characteristics of SHM systems and, in particular, the structures being monitored [40].

The **Semantic Sensor Network (SSN)** ontology has been developed by the W3C Semantic Sensor Network Incubator Group to describe sensors and sensor networks [41]. The SSN ontology is compatible with the OGC standards, without being constrained by these standards. The SSN ontology is a domain-independent metamodel that merges three different views, sensor-focused, observation-focused, and system-focused. The SSN ontology is capable to describe sensor accuracy and capabilities, observations and methods used for sensing as well as deployment life time and sensing purpose. The ontology may be used from four different perspectives or a combination of perspectives. The first perspective is related to sensors, in which the focus is put on what is sensed and how it is sensed, while the second perspective is based on observations and metadata related to observations. The third perspective is a system perspective that describes sensor systems, and the fourth perspective is a feature and property perspective, in which features, properties of features, and entities that can sense the properties are described (e.g. a feature is wind, the properties are wind speed and wind direction, and the entity is an anemometer). Limitations of the SSN ontology are measurement units, locations, and time series. To overcome these limitations, other ontologies may be included and combined with the SSN ontology.
Other sensor modeling approaches have been proposed, as summarized in [42], such as Device Kit, Device Description Language (DDL), Energy Conservation and Homecare Network (ECHONET), and a novel approach labeled “seven-layer sensor model”. The seven-layer model, composed of the following layers, provides a semantic description of issues related to physical sensors, i.e. operating environment description, physical description, unit and block description, event and protocol description, functional description, network communication and protocol description, and interoperable data service description. In [42], five sensor models are analyzed, ranked and described (Device Kit, DDL, ECHONET, IEEE and SensorML). According to the ranking presented in [42], the IEEE 1451 standards family and SensorML have been found most appropriate for describing sensors.

In summary, the ontologies and description languages presented above are capable to describe sensor characteristics, e.g. sensing devices and hardware compositions. Limitations are obvious if network descriptions are involved. Nevertheless, the IEEE 1451 standards family and the SSN ontology are powerful tools to overcome the lack of network descriptions. In terms of measurements descriptions, O&M and SensorML are description languages that may be used to describe measurements. However, certain characteristics of SHM systems are not covered by the languages reviewed, e.g. embedded algorithms, overall SHM strategies, diagnosis levels, and histories of sensor installations and configurations.

5.3 BIM-based metamodels

In recent years, building information modeling has become the state of the art in the AEC industry to describe information about structures [43]. BIM supplements three-dimensional geometric models with semantic information of buildings and structural components. Based on predefined object-oriented classes introduced to store information relevant to building and structural components, a plethora of information from different disciplines can be described using BIM. However, because of the absence of modeling capabilities for describing monitoring-related information, BIM-based
descriptions of SHM systems are still immature. Delgado et al. have examined capabilities of existing open BIM standards, concluding that extensions of the standards are needed to enable proper documentations and information exchange of SHM systems [40].

In the following paragraphs, BIM-based metamodels are presented focusing on specific monitoring-related modeling aspects. First, modeling capabilities regarding infrastructure and maintenance of infrastructure are addressed. Then, extension mechanisms of BIM-based metamodels are discussed to overcome the absence of modeling capabilities for monitoring-related information. Next, the use of BIM-based metamodels in the operation and maintenance phase of structures is reviewed. Finally, the approaches are summarized and a conclusion is drawn.

Huston et al. present a two-pronged approach to develop a framework that uses BIM as a backbone for SHM and maintenance issues [29]. For the first prong, a top-down approach is chosen starting with low-level descriptions of sensors and repair designs. Then, medium-level descriptions of sensor data mapped on structural components are added and, finally, high-level analysis and decision-influencing descriptions complete the first prong. For the second prong, field tests on bridges and buildings are used to enhance the framework in a bottom-up approach. With the two-pronged approach, information is organized, improving the process of designing and planning SHM systems, which are typically created in manual and time-consuming processes, considering various kind of different information sources, e.g. for visual inspections, for sensor data, or for structural configurations.

According to whether BIM processes are attuned to the same software family or to cross-software applications, BIM processes are classified as “closed BIM” or “open BIM”. While an exchange of models between planners in closed BIM processes is typically coordinated through a proprietary format, data exchange in open BIM processes is coordinated through open, standardized formats, such as the Industry Foundation Classes (IFC) [44]. The IFC have primarily been designed to describe information related to buildings. However, with the ongoing trend of using BIM in the planning phase, in the construction phase, and, nowadays, also in the operation and maintenance phase of buildings,
several research projects are dealing with extensions of the IFC to infrastructure objects, such as bridges, roads, railways, and tunnels [45-49], some of which to be implemented in the next version of the IFC standard (“IFC5”) [50]. Considering SHM systems as a specific type of infrastructure, it is appropriate using the IFC to describe SHM systems. However, due to the absence of IFC modeling capabilities for SHM systems, a comprehensive IFC-based description of monitoring-related information is hardly possible.

A distinct advantage in modeling building information and monitoring-related information with IFC is the description of information in a single model based on a uniform and consistent metamodel. To overcome the absence of modeling capabilities, Delgado et al. [51] have proposed using proxy elements and user-defined property sets to describe information beyond the current scope of IFC. However, because of ambiguous and non-standardized nature of proxy elements and user-defined property sets, an exchange of information may result in a loss of semantic information. To advance the description of objects, properties, and processes independent from natural languages, data dictionaries, such as the buildingSMART Data Dictionary (bSDD) [52] and information delivery manuals [53], may contribute to compensate ambiguities of proxy elements and user-defined property sets. However, data dictionaries and information delivery manuals are not available in every software product and, since data dictionaries and information delivery manuals solely cover distinct domains of interest, the description of monitoring-related information still may be ambiguous due to the cross-domain nature of the information. To overcome the ambiguity, Theiler and Smarsly have proposed an extension of the IFC schema, referred to as “IFC Monitor” [54]. With the IFC Monitor extension, monitoring-related information in the context of structures being monitored can be described based on an established open BIM format. Therefore, classes, types, and domain rules for SHM systems that could not be described using the current IFC version have been identified and added to the IFC schema.

Employing BIM is of particular benefit when building information models are used in the long term in the operation and maintenance phase of complex structures. Therefore, Aruga and Yabuki have proposed a semantic model for describing information about the degradation of structures in operation
and management [24]. The semantic model is capable to describe information for exchanging cooperative information and decision making in maintenance management between planners and public authorities.

Chen et al. have introduced a so-called “dynamic BIM framework” for connecting sensor data with IFC-based BIM models to enable access to accurate information about the state of facilities [30]. The dynamic BIM framework allows facility managers accessing and visualizing BIM models enriched with real-time data of components collected by sensors. Although the dynamic BIM framework connects real-time sensor data with information of BIM models, it does not provide possibilities to describe monitoring-related information. Other approaches are pursuing extensions of the IFC schema with sensor-related information, e.g. Rio et al. [55] propose adding further types for sensors. However, solely adding new sensor types to the IFC schema does not solve the issues originating from the absence of modeling capabilities for monitoring-related information.

Another metamodeling concept frequently associated with the BIM approach is the digital twin concept, which is a digital representation of a coupled system covering not only the physical object itself, but also processes running virtually in the system, for example control process in SHM systems. Although the digital twin concept shares a lot of similarities with the BIM concept, the term “digital twin” originally refers to a more general modeling concept covering not only metamodeling of an engineering system, but also integrating simulation platforms, such as Modelica, into the concept [56, 57]. Thus, creating a digital twin of a SHM system would require not only metaization concepts addressed in this paper, but also prototyping the SHM system in the simulation software, which goes beyond the scope of the paper.

In summary, describing SHM systems using BIM is promising. However, in common BIM approaches, a lack of modeling capabilities for SHM systems is inherent, because BIM has been developed for describing buildings rather than SHM systems. The description of monitoring-related information has mostly been out of the scope of BIM, which, however, has changed in recent years,
and recent research work increasingly deals with describing SHM systems with BIM. Here, the main weakness is the lack of open BIM formats for describing SHM systems that advance documenting and exchanging SHM models. Recent efforts propose extending the current standards. However, the extensions focus on specific issues when describing SHM systems with BIM, e.g. by solely adding new sensor types. Although the extensions are capable to solve the issues in the short term with workarounds or changes in open BIM formats, in the long term it is important to develop metamodels able to fully describe SHM systems using BIM.

5.4 Mathematical approaches

As described earlier, it is evident that further development of SHM modeling methodologies requires mathematical formalisms suitable to consistently describe SHM systems. Thus, key directions related to applications of mathematical formalisms towards describing SHM systems, and SHM modeling respectively, are described in this subsection. A major portion of this subsection is devoted to wireless sensor network modeling, because wireless sensor networks represent a key technology increasingly deployed in SHM [58].

The behavior of SHM systems and SHM system components in civil engineering is characterized by strong interactions and, therefore, by a high degree of coupling. Thus, abstract mathematical modeling methodologies must provide sufficient expressive power to describe individual components of SHM systems as well as couplings among the components. Moreover, one goal of abstract modeling methodologies is the detection of modeling errors. Modeling errors may be classified into two principal classes, (i) errors related to abstract modeling, e.g. conceptual errors concerning the coherence of the model as a whole or the underlain metamodel, and (ii) errors related to the practical realization of models, e.g. questions of approximation quality and implementation. While errors related to practical realization of models are well understood, the conceptual errors (often related to metamodelling) are not well studied. The interested reader is referred to [59] for a detailed discussion.
In [60], an abstract modeling methodology based on category theory has been proposed. Category theory is used as a mathematical language to formally describe the models and the model couplings. Moreover, by using categorical constructions, models may be structured and evaluated with respect to complexity. In addition, the coherence of coupled models may be checked within the framework of category theory. Based on theoretical results related to the category theory-based modeling methodology, the modeling methodology has been applied to other SHM-related engineering applications. For example, first steps towards categorical formulations of cyber-physical systems have been addressed in [61], and in [62] the application of category theory-based modeling methodology to aerodynamic modeling of bridges has been presented.

Another approach to abstract modeling is to adopt tools of set theory and abstract relational algebra, which is very natural in general system theory [63, 64]. Considering modern SHM systems a specific type of cyber-physical systems, the approach presented in [65] is promising to advance SHM system modeling. Set theory and abstract algebraic approaches to describe components of a cyber-physical system (CPS) and coupling between the CPS components have been used in [65]. However, this approach is more focused on a formal description of the computational parts of cyber-physical systems or SHM systems without allowing for complete descriptions of the entire system. Another abstract algebraic approach to conceptual modeling of intelligent structures has recently been proposed in [66]. Starting from an abstract definition of sensors and sensor networks, a principal structure of intelligent systems has been derived. Moreover, the conceptual approach proposed in [66] has been validated on a practical engineering example.

With the development of modern sensing technologies, wireless sensor networks (WSN) are increasingly employed in SHM systems, rendering WSN a major part of SHM design. Nowadays, two
main mathematical formalism used for WSN modeling exist, (i) models based on graph theory and (ii) models based on game theory, as illustrated in the following paragraphs.

**Graph theory** has been used since many years in theoretical computer science for organizing computer data structures [67]. With the introduction of WSNs, it has been noticed that the topology of a sensor network can be described as a graph, where vertices are nodes of the network and edges are wireless links between the nodes [58]. Once establishing a general framework for graph theory-based WSN modeling, more advanced methodologies and techniques well-established for the classical graph theory can be applied. For example, an improvement of WSN energy consumption models based on random graph theory has been proposed in [68], and a more abstract operator calculus approach for path optimization in WSN has been proposed in [69]. In addition, the interested reader is referred to [70] for a detailed review on applications of graph theory to WSNs. Although there are advantages of using graph theory for WSN modeling, the results reported so far only cover parts of SHM systems. Modeling of complete SHM systems using solely graph theory has not been proposed so far.

In contrast to graph theory, **game theory** has been mainly utilized in economics, politics, and sociology, rather than in computer science. It has been found that game theory may be used in WSN modeling to analyze interactions among sensor nodes [71]. Moreover, given that WSNs typically have limited resources in terms of energy or bandwidth, classical game theoretic settings are reflected in WSN setups, where each “player” (i.e. a sensor node in a WSN) has its own interest and strategy. Thus, game theory has been applied to WSN modeling to address problems such as power control or energy efficiency [71, 72]. Unfortunately, game theory shares the limitations of graph theoretic approaches to WSN modeling, because game theory does not address complete SHM systems but only components of SHM systems that are represented by WSNs. Therefore, complete mathematical descriptions of SHM systems are not fully possible only by game theory.

In summary, several approaches to abstract modeling of engineering systems by means of category theory, set theory, and type theory have been proposed by several authors in recent years. Although
SHM modeling has not been addressed directly by these abstract modeling methodologies, there is hope that full descriptions of SHM systems may be done on a sound mathematical basis therewith. However, practical realization of SHM modeling by abstract approaches is still an open task. Also, mathematical formalisms currently utilized in WSN modeling lack the expressive power for a complete description of SHM systems (i.e. monitoring-related information). The main reason for the limitation is that approaches based on graph theory and game theory focus on WSN modeling rather than on metamodeling of complete SHM systems.

5.5 Coupling of metamodels

As shown in the previous subsections, there are no metamodels available capable to describe all aspects of monitoring-related information. Although approaches exist towards extending current metamodels to provide distinct modeling capabilities for specific purposes, the state of development has not reached a level that allows describing SHM systems in all aspects. Thus, as presented in the following paragraphs, several research projects work on coupling metamodels rather than on extending metamodels.

Providing capabilities to describe sensor-related information (not to be confused with monitoring-related information) on the one hand and building information on the other hand, Liu and Akinci have proposed an approach to couple SensorML with IFC [73]. While with SensorML detailed information about sensors and sensor properties are described, IFC describes the building that is monitored and the sensor locations within the building. For coupling, SensorML entities describing sensor system components are linked with IFC entities describing sensors in building information models. For validation, in a prototype application a model editor has been developed for modeling and visualizing sensor systems in buildings.

In a study reported by Jeong et al., a framework is presented, coupling different metamodels to describe monitoring systems deployed to bridges [74]. Bridge structures are described using the
openBrIM consensus standard, an open standard to describe bridge-related information [75]. In addition, openBrIM is extended for describing loads and analysis conditions relevant to finite element analyses of bridges. For describing sensor-related information, SensorML is included in the framework. The framework employs a database system installed on a central server to collect bridge information from bridge designers (e.g. geometries, engineering models, or sensor information), sensor data from on-site sensor networks, and inspection information from bridge inspection recording tools. For accessing the information and data in the database system, application programming interfaces are provided. Therewith, CAD software, engineering analysis tools, sensor data analysis modules, and web user interfaces may access the information and data.

In a case study conducted by Valinejadshoubi et al., BIM software is applied for managing information of structures instrumented with SHM systems [76]. By linking external resources, information about sensors and sensor data is managed. The linking has been realized using an add-in for BIM software that allows setting references of BIM objects, here sensors, to external files, such as images or spreadsheets. Therewith, additional information may be organized and coupled with BIM objects. Although this approach has advantages, the additional information is still unstructured and stored in data formats that are not necessarily further defined, which does not promote automated processing of the information.

In research conducted by Voss & Overend, IFC models are coupled with external databases [77]. Information that cannot be described with the IFC schema, such as information required to describe manufacturing processes of curved glass panels for facades, is stored in external databases. Linking external facade panel manufacturing information with IFC using IFC property sets demonstrates a linking mechanism that could be used for monitoring-related information. However, despite its benefits, the non-standardized way of linking and describing external information is, with respect to metamodel coupling considered here, brings with it a disadvantage in that it is not possible to exchange information between software of different vendors.
In the Ph.D. dissertation of Fuchs, a cross-domain approach is presented coupling interdisciplinary processes in the AEC industry using a multi-model concept [78]. The multi-model concept avoids a leading or integrating data schema. Rather, various metamodels are loosely and temporarily coupled using an external ID-based link model. The link model controls the relations between model components across all metamodels. The advantage of this concept can be seen in the loose linkage of the metamodels, i.e. the metamodels, complementing each other, remain unchanged. However, certain information may be redundant. In addition, with each metamodel added to the multi-model container, efforts of implementing the framework increase, due to the diversity of metamodels. In recent years, following the cross-domain approach, standardized formats, such as the multi-model container (MMC) [79] or the BIM LV container [80], have been developed.

Quality assessment of metamodel coupling has been addressed in [81, 82]. Coupling of metamodels has exemplarily been addressed by coupling of two software applications transferring a complex CAD model from one to another. Different coupling strategies have been studied, and a schema mapping has been utilized to assess the quality of data transfer. Furthermore, a generic a priori approach to assess coupling quality for data structure-based coupling is proposed, operating on the schemas involved in software to be coupled and considering various mapping patterns. The coupling quality is evaluated within a formalization process by considering different sources of mapping errors.

6. Results and discussion

In this section, conclusions are drawn based on the summary review, and an approach towards developing a robust formalism to semantically describe monitoring-related information is presented. Precise description of information on SHM systems may advantageously influence the process of planning, operating, and maintaining SHM systems. Ideally, common metamodels should be used as a formal basis for exchanging information between all parties involved in planning, operating, and maintaining SHM systems. Therefore, monitoring-related information arising from different domains,
as illustrated in Section 3 and Section 4, needs to be described on a sound basis. Metamodel-based architectures and approaches, providing capabilities to describe monitoring-related information in single metamodels have been summarized in Section 5. However, the current status of development of metamodel-based architectures and approaches is not sufficient to fully describe SHM systems. Currently, there is no metamodel available that can be used to describe monitoring-related information in full detail. While specific, single aspects may be described sufficiently, other aspects cannot, or only rudimentarily, be described. For example, using SensorML, sensors and processes related to sensor measurements can be described, but the structures being monitored are not considered. Vice versa, the IFC standard, for example, provides extensive capabilities to describe the structures, but sensors and processes as well as monitoring-related information are not considered sufficiently.

Provided that a set of domain-specific metamodels serving specific domains, referred to as “partial metamodels”, is available instead of a single global metamodel, domain-specific metamodels may be coupled to achieve a global description of SHM systems (Section 5.5). However, currently no metamodels are dedicated to the description of monitoring-related information that go beyond the description of sensor-related information. Thus, developing a metaization concept using coupling mechanisms requires, in a first step, developing a metamodel that considers all aspects of monitoring-related information.

In consequence, to provide a metamodel for monitoring-related information, either (i) a novel metamodel needs to be developed, or (ii) existing metamodels need to be extended. For developing a novel metamodel, general meta-metamodels (Section 5.1) may serve as a basis. For extending metamodels, either SHM-related ontologies and description languages (Section 5.2) or BIM-based descriptions (Section 5.3) may be extended. In addition, rendering the approach more robust, mathematical concepts may be applied (Section 5.4). Novel or extended metamodels may serve as a basis to provide a metaization approach dedicated to describe monitoring-related information either (i) in a single global metamodel or (ii) as a partial metamodel that is coupled with other partial metamodels. Both approaches (i.e. a global metamodel or coupled partial metamodels) show distinct
advantages and disadvantages, as discussed above. As a result of the summary review, it is concluded that both approaches are promising for describing monitoring-related information (Figure 5).

1. **Coupling of metamodels that either exist (and need to be extended) or that have to be defined from scratch.** In particular, a partial metamodel with regard to monitoring-related information is to be defined that may be coupled with other partial metamodels, e.g. for structural analysis.

2. **Developing a global metamodel (e.g. based on open BIM standards).** An extension of an existing metamodel (e.g. an open BIM standard) may serve as a formal global metamodel for describing monitoring-related information in the context of structures being monitored.

![Diagram showing approaches for describing monitoring-related information](image)

**Figure 5:** Approaches for describing monitoring-related information: a) Approach 1: Coupling of metamodels that either exist (and need to be extended) or that have to be defined from scratch; b) Approach 2: Developing a global metamodel (e.g. based on open BIM standards).

This study recommends pursuing both approaches and eventually comparing the results. However, regardless of the approach adopted, a mathematically sound concept should serve as a formal basis for describing monitoring-related information. In addition, the metamodeling approach towards
monitoring-related information must be validated in real-world scenarios, providing insights into robustness and scalability.

7. Summary and conclusions

SHM systems are widely used to assess the condition of civil infrastructure. SHM systems involve various hardware and software components, such as sensing hardware, communication devices, and sensor data. Information on SHM systems is referred to as “monitoring-related information”, and it includes, for example, information about the semantic composition of SHM systems, about the embedded algorithms used in sensor nodes for data analysis, or about the topology of sensor networks and the communication between sensor nodes. Formal descriptions of monitoring-related information are a step towards optimization of SHM systems, documentation of SHM system components, and tracking changes of the systems throughout the life time. However, existing approaches may describe parts of monitoring-related information but are unable to capture all monitoring-related information required to fully describe SHM systems. In this paper, a summary review of modeling approaches for monitoring-related information has been presented. The methodology used for analyzing information sources from different domains is based on a three-pillar concept. First, standards, recommendations, and guidelines related to SHM systems have been summarized and the information extracted from the summary is hierarchically structured. Then, information not covered by existing modeling approaches has been collected and described and as well hierarchically structured. Finally, existing ontologies and modeling approaches related to SHM systems have been analyzed, specified and described, considering BIM-based approaches, mathematical approaches, and coupling of metamodels.

From the summary review presented in this paper, it is concluded that a complete description of SHM systems on a sound basis is still an open research question. Existing metamodels and ontologies may be used to describe a subset of monitoring-related information but not all monitoring-related information. A complete description of SHM systems taking into account all monitoring-related information may be achieved (i) either by coupling metamodels, which exist (and need to be extended)
or that have to be defined from scratch, (ii) or by developing a global metamodel, e.g. based on open BIM standards. With a formal and complete description of SHM systems, optimization, documentation and change tracking of SHM systems are possible and uncertainties, such as quality of sensor data, may appropriately be analyzed and assessed. Further research related to SHM systems description may focus on both approaches discussed above.

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