Parametric Information Modeling of Cyber-Physical Systems based on Industry Foundation Classes

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Abstract

Parametric modeling employed in designing cyber-physical systems facilitates semi-automated model adaptations. Through semi-automated model adaptations, model parameters can be modified with regard to performance, reliability, or robustness, which improves cyber-physical system design, thus enhancing cyber-physical system quality. Using conventional design software, cross-software exchange of parameterized, non-parametric building information (e.g. non-parametric geometry, material or cost) is supported by open building information modeling (BIM) standards, such as the Industry Foundation Classes (IFC) standard. However, cross-software exchange of parameterized and parametric information (e.g. parametric geometry constraints) still poses an open research problem. Although the IFC standard provides an open, parameterized data format for exchanging building information, the description of parametric information with the IFC schema is limited. In this study, a conceptual approach towards BIM-based description of parametric information is presented. Based on modeling languages, ontologies, and research approaches describing parametric information, the conceptual approach emphasizes semantic modeling of cyber-physical systems. Focusing on structural health monitoring (SHM) and structural control applications, the conceptual approach serves as a formal basis to extend the current IFC schema, enabling BIM-based description of parametric information, including information on system dynamics, such as system states and algorithms dynamically adapted to environmental and structural conditions. As a result, parametric information of cyber-physical systems designed for SHM and structural control applications, as well as the dynamics inherent to the systems, can be described in IFC-compliant building information models.

Keywords: Parametric information modeling, cyber-physical systems, building information modeling (BIM), structural health monitoring (SHM)

1. INTRODUCTION

Quasi-automated, self-regulating optimization strategies in engineering have paved the way for efficient and sustainable engineering applications (Smarzly et al., 2011). Sanfelice (2016), for example, has proposed deploying cyber-physical systems for merging engineering applications and processes of the digital and the physical (real) world. The term “cyber-physical system” (CPS) refers to engineering systems integrating physical processes with computational and networking processes. Using intelligent, networked processes and methodologies, so-called “smart” structures, i.e. structures instrumented with control and self-regulating abilities (Casciati & Chen, 2012), enable real-time adjustments of CPS processes. Shaped by the digitization ubiquitous in engineering (“Industry 4.0”), several engineering applications, such as wind turbines instrumented with intelligent monitoring and control systems accessible through online cyber infrastructures (Smarzly & Petryna, 2014; Smarsly et al., 2007, 2012), showcase the potential of cyber-physical systems for optimizing physical processes in interaction with processes from the digital world.

When designing cyber-physical systems, different model variants are examined, e.g. with regard to performance, reliability, and robustness (“target variables”). Therefore, input variables of cyber-physical systems, such as number and locations of sensors and actuators, are optimized, and the quality of the model variants is assessed with respect to the target variables. In addition, in the design phase, different partial CPS models are considered that make up a global model of a CPS. For semi-automated optimization of cyber-physical systems, the input variables are first parameterized and then varied within previously defined thresholds, taking into account predefined boundary conditions and dependencies between components of the systems. Because many designers from different disciplines as well as heterogeneous models are typically involved in the CPS design process, information exchange without loss of semantic information between designers is essential to achieve high-quality systems optimized with respect to the target variables. However, to achieve information exchange without information loss, precise descriptions of CPS information are required. Due to the heterogeneity of disciplines and models involved in the CPS design process, there are discrepancies between discipline-specific models. To overcome these discrepancies, Wawrzik et al. (2015) have proposed a generic inter-system
methodology based on the Systems Modeling Language (SysML) standard (ISO, 2017), which provides a graphical modeling language based on the Unified Modeling Language 2 (UML 2) standard (ISO, 2012). The inter-system methodology allows capturing and managing uncertainties in models of cyber-physical systems (Radojicic et al., 2017). However, due to the generic approach, the methodology differs significantly from conventional ways of describing structures, and integrating the methodology into the CPS design process still poses an open research issue.

In the construction industry, building information modeling (BIM) has become the state of the art providing means widely used to describe information about structural systems, such as buildings or infrastructure systems (NIBS, 2015; CEN, 2015). BIM technology forms a solid basis for documenting and exchanging building and infrastructure information, containing 3D geometric information supplemented by semantic information of the structural components (Eastman et al., 2011). With BIM, different kinds of information from different disciplines can be described in an object-oriented manner. Thus, BIM provides an attractive formal basis to describe cyber-physical systems.

Depending on whether BIM processes are attuned to the same software or to cross-software applications, BIM processes are classified as “closed BIM” or “open BIM” (Bormann et al., 2015). In closed BIM processes, information exchange between designers is typically coordinated using proprietary file formats. Although software vendors offer a variety of software for modeling and simulating structures, not all applications can be covered by one software vendor. For applications that are not covered, the proprietary file formats used must be converted into other formats to enable information exchange, which may cause semantic information loss. In open BIM processes, to avoid semantic information loss, information exchange between different software is coordinated using open file formats, such as the Industry Foundation Classes (IFC) standard (ISO, 2013). With the IFC, semantic building and infrastructure information can be comprehensively described, adopting an object-oriented approach with predefined sets of types, entities, rules, and functions to capture information in all life-cycle phases of a structure.

The description of cyber-physical systems, as proposed by Smarsly et al. (2017), can be implemented using an extension of the IFC schema, the extension serving as a metamodel to describe building and infrastructure information. With the IFC extension, an IFC-compliant description of CPS-related information, such as information on sensor node design, algorithms embedded into sensor nodes, configuration and topology of sensor networks, or overall monitoring and control strategies, is provided on a well-defined formal basis (Legatiuk et al., 2017a,b). By using IFC to describe CPS-related information, all information needed for well-defined descriptions of cyber-physical systems is contained in single IFC models. By contrast, further recent approaches towards describing CPS-related information combine different ontologies and metamodels with self-defined semantic models. Jeong et al. (2017), for example, propose an inter-system framework for achieving loosely coupled, partial CPS models. Although CPS-related information can be described with inter-system frameworks, the frameworks are characterized by different technologies and formats, which may lead to redundant, non-uniform or out-of-context description of information that might result in a loss of semantic information.

In addition to CPS-related information, information about input variables of cyber-physical systems (“parametrized information”) as well as information about predefined boundary conditions and information about dependencies between components within a CPS (“parametric information”) need to be formally described aiming to exchange semantic information about parameterized and parametric information. While the process to create parameterized and parametric models, referred to as “parametric modeling”, is supported by an increasing number of design software (Boeykens, 2012), formal descriptions of parameterized and parametric information, hereinafter termed “parametric information modeling”, has received little attention. As long as parametric information modeling is processed within the same software (closed BIM), exchange of parameterized and parametric information is possible without information loss. However, cross-software exchange of parameterized and parametric information (open BIM) is usually not supported by software vendors, due to the absence of open data formats for parametric information modeling (Humphp and Österlund, 2016).

In the construction industry, parametric modeling, originally stemming from the machine and aircraft industries, is gaining increasing importance. To describe parametric information that can be used for documentation and for information exchange of bridge models, Ji et al. (2013) have proposed an extension of the IFC schema. Focusing on sketch-based approaches for parametric modeling, the IFC extension introduces more than 40 entities to describe constraints and equation-based relationships between input variables. However, in the IFC extension approach, entities of the official IFC standard capable to describe parametric information, which are discussed in the following section in more detail, are not considered. By contrast, Cheng and Wu (2013) have presented a methodology for exchanging parametric information using a middleware concept, referred to as “BIM object adapter”, which builds upon an object-oriented approach based on the IFC. Using application programming interfaces, the exchange of parametric information between heterogeneous software is implemented aiming to
increase data integrity and to reduce transfer and integration time. However, due to middleware concept, open access to parametric information is not enabled; rather, for each software, separate middleware components must be developed to enable information exchange. Humpii and Österlund (2016) have proposed a modeling concept for connecting common practices of BIM with algorithm-aided design enabling designers to create parametric geometry models enriched by semantic information that is related to geometry objects contained in models.

Focusing on CPS applications in structural health monitoring (SHM) and structural control, this paper presents a conceptual approach serving as a formal basis for BIM-based descriptions of parameterized and parametric information relevant to cyber-physical systems (CPS-related information). In the conceptual approach, parameterized and parametric information is systematically classified and mapped into a semantic model to technology-independently describe parameterized and parametric information. Mapping the semantic model into an extension of the IFC schema, describing parameterized and parametric information relevant to cyber-physical systems is advanced using an open BIM standard. Finally, the IFC extension is verified and validated to ensure IFC compliance. The paper concludes with a discussion and a summary of the results expected.

2. PARAMETRIC MODELING

This section summarizes and categorizes parametric modeling approaches, followed by a concise overview of parametric modeling capabilities of BIM, with particular emphasis on the IFC. In parametric modeling, components of structures are designed with dependencies, referred to as “constraints”, with respect to input variables, referred to as “parameters”. Constraints can be categorized by the type of information the constraints denote, such as topological constraints, dimensional constraints, physical constraints, and process constraints: Topological constraints determine relative placements of components, e.g. two lines being parallel or perpendicular to each other; dimensional constraints determine geometric properties of components, such as lengths, distances, or plane angles; physical constraints determine physical properties of components, e.g. defining materials or loads; and process constraints determine properties related to the construction of components, such as tolerances. Topological constraints and dimensional constraints are typically used to allow designers specifying morphological design intents, while physical constraints and process constraints are used to manipulate stability and constructability of structures.

To categorize parametric modeling approaches, Ledermann et al. (2005) have proposed a categorization with regard to stages of morphological transformations characterizing the modeling capabilities of constraints and parameters. As illustrated in Figure 1a, the first step towards parametric modeling is to introduce parameters for “fixed objects”. Here, two parameters, width \( w \) and height \( h \) describing the shape of a rectangle, are added to the fixed object. As a result, “parameterized objects” enable changing the object properties by modifying the parameters (Figure 1b). However, parameterized objects cannot be used to specify all constraints, for example assuming \( h \) to be twice the length of \( w \), because height and width of the rectangle are independent from each other. Thus, in the next step towards parametric modeling, constraints are introduced, which are mapped based on equations, entailing “equation-based parametric objects” (Figure 1c). As shown in Figure 1c, the ratio between width and height of the rectangle is expressed by \( h=2w \). In a further step, shown in Figure 1d, the level of morphological transformations is increased using script-based statements to express advanced constraints allowing logic reasoning to be included resulting in “script-based parametric objects”. In Figure 1d, a conditional statement is used to describe the height of the rectangle, which is either twice the width, if the condition \( w<2 \) is met, or it is set to a length of three length units, if the condition is not met. Parameters independent from other parameters are typically referred to as “primary parameters”, whereas parameters that depend on other parameters are referred to as “derived parameters”. To change parametric models, solely primary parameters are modified, because derived parameters are automatically calculated by parametric modeling tools based on constraints with regard to primary parameters or to other derived parameters.

Besides morphological transformations, topological transformations are common in parametric modeling. Topological transformations allow instantiating objects, i.e. the number of objects to be created is modeled either manually or automatically by parametric modeling tools. The level of morphological transformations provided by parametric modeling tools can be assessed (in ascending order) with manual instantiation, automatic instantiation, generic manual instantiation, and generic automatic instantiation. Manual instantiation allows designers to copy objects manually. Automatic instantiation allows designers performing multiple copy operations in one step. The number of instances to be copied is, therefore, specified parametrically. Generic instantiations extend copy operations by adjusting objects to be copied according to context-dependent boundary conditions, for example, by adjusting the size of objects to available space at insertion points. Depending on whether extended copy operations are performed manually or automatically by parametric modeling tools (based on predefined functions describing the boundary conditions), copy operations are categorized into generic manual instantiations and generic automatic instantiations, respectively (Amadori et al., 2012).
Using parametric modeling results in flexible models, sometimes referred to as “smart models”, because the models contain knowledge based on construction rules (constraints) materialized in a few primary parameters (“knowledge-based parametric models”). The models can quickly be adapted to changing boundary conditions, thus taking into account the dynamics of the system being modeled. In addition, by varying the primary parameters of the models, a large number of model variants are easily created and, in conjunction with optimization tools, the optimum solution with respect to target variables is evaluated. For example, the Beijing National Stadium and the Shanghai Tower are developed using parametric modeling tools providing optimized solutions with respect to design, to environmental boundary conditions, and to versatility of use (Designing Buildings Ltd., 2017). In architecture, parametric modeling tools have paved the way to “parametricism” movement, a theory-driven design movement that uses algorithms to design complex structures semi-automated based on predefined constraints (Schumacher, 2016). The following subsection focuses on parametric modeling capabilities in the context of BIM.

![Diagram of morphological transformations](image)

Figure 1. Stages of morphological transformations: (a) Fixed objects, (b) parameterized objects, (c) equation-based parametric objects, and (d) script-based parametric objects

### 2.1 Parametric modeling and BIM

Parametric modeling can be integrated into BIM software as a useful concept to develop “smart” building information models, which contain dependencies to determine design intents related to geometric properties and to non-geometric properties. However, BIM software provides parametric modeling concepts only to a limited extent. For example, parametric modeling concepts are used to create parameterized types representing building components, and most BIM software provides modeling capabilities to implement topological and dimensional constraints (Borrmann et al., 2015). On the other hand, in contrast to parametric modeling software, BIM software usually offers only limited capabilities for developing free-form geometries for cross-component designs, which can be achieved through integrated scripting, through visual programming, or through dataflow modeling. Thus, in BIM software the dependencies are mostly used on an object-level, while in parametric modeling software the overall models become single assemblies due to complex dependencies between the components. However, through the object-based approach, BIM software provides means to describe structured models and to embed semantic information relevant to building components. In contrast, parametric modeling software is used to create “pure” geometry models with minimal semantic information (Boeykens, 2012).

From a technical perspective, BIM is inherently parametric, because BIM provides descriptions of parameterized objects with certain intelligence embedded, such as automated intersections of walls at connection points. When parameters of BIM objects are modified, the modifications can lead to further changes due to dependencies between the objects. Thus, building information models can be referred to as “object-based parametric models” (Eastman et al., 2011). For example, if walls are assigned to stories, each wall spanning the entire height of the story it is associated with, modifications of story heights automatically lead to modifications of wall heights.

Therefore, BIM comprises a set of predefined types, also labeled “families”, that contain type-specific dependencies with regard to other types. In the following subsection, capabilities for parametric information modeling using the Industry Foundation Classes are summarized.

### 2.2 Parametric information modeling using the IFC

To a limited extent, the IFC schema provides capabilities for describing parametric information (buildingSMART, 2016). As illustrated in Figure 2, constraints (subtypes of the IFC entity IfcConstraint) are associated with objects (subtypes of IfcObjectDefinition) or with properties (subtypes of IfcPropertyDefinition) using IfcRelAssociatesConstraint relationship entities. The relationship entities indicate certain intents to be achieved with associations. Describing constraints, the abstract IfcConstraint entity comprises attributes (i) to assign human-readable names and descriptions to constraints (“Name” and “Description”), (ii) to qualify constraints, e.g. whether constraints must be met, should be met, or are advised to be met (“ConstraintGrade” and “UserDefinedGrade”), (iii) to assign any source material, such as codes or standards, from which constraints
originate (“ConstraintSource”), and (iv) to assign information about the creation of constraints (“CreatingActor” and “CreationTime”). In the IFC schema, two subtypes of constraints, metrics (IfcMetric) and objectives (IfcObjective), are distinguished. While metrics are used to capture quantitative information of constraints (such as dimensional constraints), objectives are used to capture qualitative information of constraints to describe certain purposes to be achieved, such as requirements with respect to compliances with codes. Therefore, both metrics and objectives describe parametric information in an object-oriented manner, which is described in more detail in the following paragraphs.

Describing quantitative information of constraints, metrics comprise (i) logical comparators (“Benchmark”), (ii) specifications of sources of values (“ValueSource”), (iii) specifications of parameter values (“DataValue”), and (iv) reference paths to attributes of objects to be constrained (“ReferencePath”). Logical comparators, such as “greater than” or “equal to”, are used to determine thresholds of parameters. Evaluating constraints, reference paths to attributes to be constrained are resolved, and the thresholds are evaluated according to logical comparators and to values specified. For example, to limit the elevation of stories (IfcBuildingStorey) to a maximum of 20 length units, the stories are associated to a metric, which has (i) a logical comparator of the type “less than or equal to”, (ii) a scalar value of 20 length units, and (iii) a reference path to the attribute “Elevation” of the IfcBuildingStorey entity.

Describing qualitative information of constraints, objectives comprise (i) lists of nested constraints capturing benchmark metrics of constraints (“BenchmarkValues”), (ii) logical operators, e.g. “and”, “or” or “xor”, to logically aggregate the nested constraints (“LogicalAggregator”), and (iii) qualifiers to determine purposes of objectives, e.g. to indicate compliances with codes (“ObjectiveQualifier” and “UserDefinedQualifier”). Using objectives allows specifying purposes of constraints and capturing benchmark metrics of constraints.

Using metrics and objectives facilitates describing constraints applied to parameters of components. Specifically, morphological transformations between parameters of components can be described through equations. As a consequence, using the current IFC schema, components associated with constraints can be considered “equation-based parametric objects” (cf. Figure 1c). However, although the IFC schema provides capabilities for parametric information modeling to describe equation-based parametric objects, conventional BIM software does not support information exchange based on these capabilities, because conventional BIM software solely focuses on domain-specific subsets of the IFC schema, referred to as model view definitions (buildingSMART, 2018). Since parametric modeling capabilities are currently out of scope of all model view definitions, exchanging parametric information between conventional BIM software using these capabilities is not supported (Mirtschin, 2014). Therefore, extending the model view definitions (or creating new model view definitions) with capabilities for parametric information modeling seems appropriate to encourage software vendors to support parametric modeling concepts in open BIM processes.

Unlike morphological transformations, topological transformations cannot be described using the IFC schema due to the absence of adequate modeling capabilities. Thus, information modeling of topological transformations based on open BIM standards is an open research issue addressed in this paper, as described in the following section, with emphasis on cyber-physical systems designed for SHM and structural control applications.
3. TOWARDS PARAMETRIC INFORMATION MODELING OF CYBER-PHYSICAL SYSTEMS

With parametric information modeling, the design process of cyber-physical systems can be improved by a sound basis for describing predefined design intents and dependencies between components of cyber-physical systems. Information both on morphological transformations and on topological transformations can be comprehensively described. In addition, using open BIM formats as a basis for parametric information modeling, cross-software exchange of parametric information is facilitated, thus enabling the use of a variety of software applications of different vendors providing distinct parametric modeling tools to optimize cyber-physical systems.

In the design phase, using parametric modeling tools enables semi-automated adaptations of CPS model variants that can be assessed with regard to target variables, such as performance, reliability, and robustness. Furthermore, in the operation and maintenance phase, parametric information modeling can be used to describe operational scenarios, e.g. tasks to be assigned to intelligent sensor or actuator subsystems in case of system failure. Further fields of application include descriptions of system state modifications, of operating instructions with regard to the modifications, and of processes and algorithms embedded into sensor nodes to be adapted to changing boundary conditions (Theiler et al., 2018).

For parametric information modeling of cyber-physical systems, comprehensive metamodels are needed capable to describe morphological and topological transformations with respect to predefined dependencies and boundary conditions, supporting designers in modeling parametric information used to define design intents or operating instructions. Besides topological and dimensional constraints, physical and process constraints are key factors in cyber-physical systems design. In addition, non-generic automatic instantiations and generic automatic instantiations of components of cyber-physical systems enables automated system adaptations depending on boundary conditions (e.g. automatically modifying number and placement of sensors and actuators based on predefined construction rules described using the metamodel).

For creating a metamodel for parametric information modeling, this study proposes a conceptual approach towards BIM-based description of parametric information relevant to cyber-physical systems designed for SHM and structural control applications. As shown in Figure 3, the envisioned approach is characterized by a five-step process joining paradigms of both modeling fields considered in this study, namely parametric information modeling and building information modeling. The five-step process includes

(i) summarizing modeling concepts of parametric information in a literature review,
(ii) semantic modeling of parametric information in an object-oriented manner,
(iii) extending the IFC schema by capabilities to describe parametric information (“Parametric IFC” extension),
(iv) verifying the extended IFC schema with appropriate checking tools, and
(v) validating the extended IFC schema by modeling prototype CPS models containing parametric information.

Figure 3. Conceptual approach towards parametric information modeling of cyber-physical systems

In step (i), on one hand, in the field of parametric information modeling, descriptions of parametric information based on modeling languages, on ontologies, on models developed in research approaches, and on models from conventional software solutions, are summarized and categorized in a literature review. On the other hand, in the field of BIM, the review summarizes capabilities for modeling parametric information both in closed BIM and
open BIM processes. In addition, modeling concepts are presented discussing methods (and methodologies) to
describe parametric information in particular with regard to the IFC schema and to extended IFC schemas from
other research projects. As a result, information characterizing parametric modeling concepts is identified and
categorized in an object-oriented manner. Therefore, the information is classified resulting in an object-oriented
metamodel (step ii), referred to as semantic model, that contains entities with attributes to describe parametric
information.

In step (iii), the semantic model is mapped into the IFC by extending the IFC schema with types, entities, rules,
and functions to describe parametric information. The IFC extension, referred to as “Parametric IFC”, aims at
supporting the documentation of parametric information and cross-software exchange of parametric information
on the basis of an open BIM standard. For verification (step iv), the extended IFC schema is checked with test
software from the official IFC certification program verifying the syntactic and semantic correctness of the
schema (b-Cert, 2018). Finally, to validate the BIM-based modeling approach of parametric information,
prototype CPS model variants are designed and evaluated based on different kind of parametric modeling
approaches, i.e. morphological transformations and topological transformations (step v).

4. SUMMARY AND CONCLUSIONS

In this study, parametric modeling approaches have been summarized and categorized, and parametric modeling
capabilities of BIM and IFC have been discussed in a concise literature review. Based on the literature review, a
conceptual approach towards BIM-based descriptions of parametric information (“parametric information
modeling”) has been presented. The conceptual approach has illustratively emphasized semantic modeling of
cyber-physical systems containing parametric information. Focusing on SHM and structural control applications,
the approach serves as a formal basis to describe parametric information relevant to cyber-physical systems
using an extension of the IFC schema (“Parametric IFC”). As a result, the approach enables BIM-based
description of parametric information, including information on system dynamics, such as system states and
algorithms dynamically adapted to environmental and structural conditions. In addition, BIM-based description
advances exchange of parametric information between software based on an open BIM standard. Thus, it is
expected that time-consuming and cost-intensive redesign processes are avoided, and, supported by
semi-automated model adaptations, alternative CPS model variants can easily be evaluated.

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