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Integrating Models of Civil Structures in Digital Twins: State-of-the-Art and Challenges

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Abstract

Software systems monitoring civil structures over their lifetime are exposed to the risk of aging much faster than the structures themselves. This risk can be minimized if we use models describing the structure, geometry, processes, interaction, and risk assessment as well as the data collected over the lifetime of a civil structure. They are considered as a unity together with the civil structure. These constitute a digital twin of such a civil structure, which through appropriate operative services remain in permanent use and thus co-evolve with the civil structure even over a long-lasting lifetime. Even though research on digital twins for civil structures has grown over the last few years, digital twin engineering with heterogeneous models and data sources is still challenging. Within this article, we describe models used within all phases of the whole civil structure life cycle. We identify the models from the computer science, civil engineering, mechanical engineering, and business management domains as specifically relevant for this purpose, as they seem to cover all relevant aspects of sustainable civil structures at best and discuss them using a dam as an example. Moreover, we discuss challenges for creating and using models within different scenarios such as improving the sustainability of civil structures, evaluating risks, engineering digital twins, parallel software and object evolution, and changing technologies and software stacks. We show how this holistic view from different perspectives helps overcome challenges and raises new ones. The consideration from these different perspectives enables the long-term software support of civil structures while simultaneously opening up new paths and needs for research on the digitalization of long-lasting structures.

Keywords: Civil Structures, Model-Based Software Engineering, life cycle, Engineering, Digital Twin, Internet of Things, Intelligent Civil Infrastructural Systems, Operations Management, Geometric Models, Modeling Smart Material, BIM, GIM, Interoperability

1. Introduction

Motivation and Relevance. In the last years, losses due to natural catastrophes have been constantly rising up to 280 billion US dollars worldwide (NatCatSERVICE, 2022; Szmigiera, 2022). Floods and storms are the leading cause of natural disaster fatalities (Doocy et al., 2013). Between 1980 and 2009 2,8 billion people have been affected by floods (Doocy et al., 2013) which represents 36 percent of the world's population. More and more people live next to coastal areas, river basins, and lakeshores which leads to a high impact of flood events on human populations causing mortalities, injuries, and displacements. Civil structures such as dams and dikes can help mitigate and prevent the effects of such flood events. Also beyond floods, civil structures like bridges, tunnels, and roads, are of great importance to our society, as they are central components of our critical infrastructures.

Digitalization is increasingly a factor in the construction and maintenance of civil structures. Civil structures, like many other constructions, are nowadays often first planned and modeled in digital form before being built in the real world. Additionally, civil structures are increasingly equipped with sensors that can provide important information on the condition of civil structures during their lifetime becoming Internet of Things (IoT) systems and intelligent civil infrastructural systems. In addition to sensor data describing the civil structures' condition, civil structures may also provide important data about the environment. Using this up-to-date data, it is possible to create Digital Shadows (DSs) or Digital Twins (DTs). This improves state assessment through regular inspection or stress simulations. In this way, they contribute, among other things, to defending against extreme environmental events, which are becoming increasingly frequent as a result of climate change.

The construction of civil structures is highly complex, since it requires expertise from many different domains, from geomechanics and mechanical engineering to business management. Software and its engineering take on several roles: (a) software is already a part of the civil structure, e.g., for controlling it, (b) DTs are software, which digitalizes other disciplines, i.e., their models and data, and (c) we need software to engineer long-lasting DTs for long-lasting civil structures. Since these disciplines have different perspectives on civil structures, the domain-specific models used to describe civil structures also deviate from each other. To effectively construct, monitor, and maintain civil structures, it is necessary to be aware of, understand, and integrate these different perspectives using software models.

Research Question and Objective. Overall, the main research question addressed in this paper is which models are needed from different research perspectives to create digital twins to improve the creation and monitoring of civil structures during their lifetime. In particular, we address the following questions:

(RQ1) **Which models are used in different domains for what purpose?** Different domains use different kinds of models and modeling languages. For example, while architects may use 3D graphical models of a civil structure when designing it, engineers may use mathematical models to estimate the stability or energy efficiency of the construction. To create an integrated understanding of civil structures, we first need to understand which kinds of models are used by experts from different domains in the context of civil structures. Next, it is important to understand why and how the models are used. Answering this enables understanding if there is an overlap between different kinds of models.

(RQ2) **Which challenges occur when integrating different modeling perspectives and generating a long-lasting digital twin for long-lasting civil structures?** Even with an integrated modeling perspective, engineering civil structures inherently remains a complex task that requires knowledge from various domains. To effectively address the remaining challenges to improve the economic, ecological, and social sustainability of civil structures in the future, we first need to identify them.

By answering these questions, the *objective* of this paper is to contribute to the effective engineering of civil structures using IoT systems connected to digital twins.

Main Contribution. We provide an overview of modeling approaches for civil structures from different research perspectives and describe their integration in digital twins to help solve challenges in the future. The research perspectives coming together in this article are structural engineering, geospatial information, building material engineering, environmental engineering, building management, and software engineering. Moreover, we show current challenges for representing civil structures in DTs and propose a research agenda.

Outline. Section 2 describes fundamentals of civil structures, their life cycle, relevant stakeholders, and modeling. Section 3 introduces models from different research perspectives and their purposes. Section 5 identifies and discusses open challenges for modeling civil structures. The last section concludes this article and shows ideas how these models can be used for improved civil structures in the future.

2. Fundamentals

We show what constitutes a civil structure, provide details about the life cycle of civil structures, and discuss different groups of stakeholders relevant to the different life cycle phases. Moreover, we introduce relevant modeling foundations relevant to different research disciplines.

2.1. Civil Structures

A civil structure is not uniformly defined throughout the literature. Some definitions of civil structures and civil engineering structures are summarized by Proske (2021). In general, a civil structure is defined as an object that is firmly attached to the ground and is made by material and labor (by humans). It is an integral part of the land and cannot be separated from the land without being damaged or changed significantly (Deutschland, 2002). According to Union (2017), a civil structure is everything that is made by construction work. Civil structures are characterized by a long lifetime, force-conducting elements, immobility, and uniqueness. They either delimit space (walls, ceilings), span space (bridges, towers), or are form-giving (monuments). Civil structures can be subdivided into *buildings* (e.g., for public, private, or industrial purposes) and *infrastructure* (e.g., bridges, tunnels, and dams). The latter is also named civil engineering structures and requires extensive structural calculations under consideration of special safety reserves (Proske, 2021). Within this paper, we are using the term **civil structure** when referring to *civil engineering structures* and *infrastructure*.

2.2. Civil Structure Life Cycle

The life cycle of constructing civil structures starts with the *pre-design and conceptual planning* phase (Figure 1, top). It covers the identification of the need for the construction as well as recommended solution options. If a solution is approved, e.g., through a feasibility study, major deliverables, as well as stakeholders, are identified and a project team begins to shape. These phases require a lot of information from different sources, e.g., geospatial datasets of the surrounding area are gathered and build often the base for subsequent planning. In the *detailed planning phase*, the construction is developed in as much detail as possible. The steps necessary to meet the construction objective are planned. If building information modelling (BIM) is used, the civil structure is modeled using components with 3D geometry and attributive information. Slices and construction plans can be derived; area, volume, and quantity measures can be calculated. Cost and time management regarding the project can be prepared. Furthermore, different simulations and variants can be analyzed and coordination and clash detection is facilitated. The following *construction* phase (Figure 1, right) covers the execution of the construction process. When bringing the design to the field, one has to transfer the civil structure design onto the land itself, thus, workers can follow it during construction. Key points and guide markers are set out to ensure accurate construction takes place. The construction progress is continuously monitored. The deviations from the original plan are recorded and the performance of the activities is measured. Corrective adjustments to the planning are made by the project manager if necessary. This phase can be supported by the BIM model. The model is used as a guideline and utilized for documentation of progress and control. Defect management can be executed efficiently. After construction, the as-built documentation can be derived from the final construction using on-site measurement techniques.

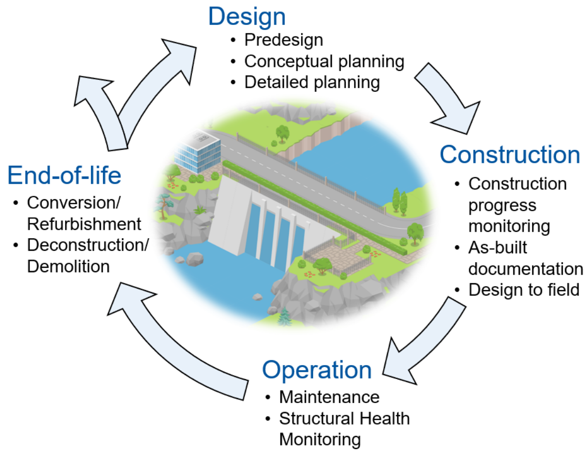

Figure 1: Life cycle of a smart civil structure (based on (Herle et al., 2020))

If available, the planned models are compared to the as-built models improving commissioning and handover. Finally, the construction can be put to *operation* phase (Figure 1, bottom), when operators and facility managers become relevant. Dam owners, e.g., electronically or hydraulically control dam gates, tend bridges, work canal locks, and lighthouses to oversee marine passage if the dam is near the shore and inland waterways. Structural health monitoring (Sakr and Sadhu, 2023) can be realized during the operation by the facility management and can be correlated with structural models to improve maintenance, ensure safety, and extend the lifetime. Currently, this is just done in exceptional cases, mostly dedicated to research. The *end of the life cycle* (Figure 1, left) comprises the demolition or the refurbishment of the civil structure. For instance, seamless documentation allows selective disassembly.

2.3. Stakeholders within the Civil Structure Life Cycle

Stakeholders are groups or individuals, who can influence or are influenced (positively or negatively) by a project, e.g., civil engineering structures. Stakeholders include project initiators (e.g., governments), users, pressure groups (e.g., NGOs and mass media), and other project-affected groups (Li et al., 2016). One can distinguish internal stakeholders (e.g., clients, developers, consultants, or contractors), external stakeholders (e.g., suppliers or local authorities), and end-users (customers or the public) (Kordi et al., 2021). Internal stakeholders can also be classified as primary stakeholders and external stakeholders and end-users as secondary stakeholders (Jansson, 2005). The participation of secondary stakeholders, particularly in the planning phase, gained importance in the past decades to increase legitimacy and acceptance (Li et al., 2016; Yang et al., 2009).

Stakeholders' roles may change within the life cycle of a civil engineering structure, especially for those with a long lifetime. For public civil structures, the government on a national or local level is the project initiator and the owner of the structure and thus responsible for the whole life cycle. Engineering companies can be involved in the design, construction, maintenance, monitoring, and, if necessary, deconstruction or reconstruction for another use (end-of-life). Different engineering companies may be contracted at different stages, requiring structured management and communication (Yang et al., 2009).

We illustrate various roles using dikes as an example. Flood protection, not only concerns those living close to the sea or river but has to manage numerous conflicting interests, resulting from the various utilization of water bodies, e.g., drinking water production, hydropower, shipping, or leisure and recreation. Additional conflicts result from the high land consumption of dikes. Therefore, the interests of various stakeholders must be considered in the construction of dikes. Case studies of stakeholder participation in water management projects are given, e.g., in (Begg et al., 2018; Edelenbos et al., 2017; Warner and Damm, 2019). Internal stakeholders in dike construction include state authorities for agriculture and environment, municipal water authorities, water or soil associations, which are responsible for approval (planning/design phase) and monitoring (operation phase), the construction industry, dredging companies, and local industry, responsible for the construction, material supply, and know-how (planning and construction phase). External stakeholders in dike construction are the affected population, the public, and governmental and university research institutions. Residents contribute knowledge of local conditions (e.g., former flood events) and report damages during the operation phase. Research institutions are integrated as consultants in the planning and operation phase, especially when the design differs from standards (Saathoff et al., 2015).

In summary, the design phase is essential for implementing various stakeholder's interests in a civil engineering project. Methods for a successful structure of stakeholder participation are given, e.g., in (Yang et al., 2009; Elmahroug et al., 2014).

2.4. Modeling Civil Structures

Models are used across research disciplines, e.g., in architecture to design and plan buildings, in business administration to plan and control construction costs, in geoinformatics to describe and understand geospatial properties and relationships, and in software engineering to design the structure, behavior, and functionalities of systems. In the specific area of Model-Driven Software Engineering (MDSE), models are used to derive software code (Combemale et al., 2016).

Despite their various applications, models share commonalities subsumed in the general model theory by Stachowiak (Stachowiak, 1973), which we define as follows:

- *The mapping property:* A model is always related to a natural or artificial original. This original in our case is the civil structure and its environment.
- *The pragmatism property:* A model fulfills its function for a specific user (group), for a certain time, and for a certain purpose. The same model can also be reused for different purposes over time, which increases the challenge of long-lasting model development.
- *The reduction property:* A model does not represent all properties of an original. We model only properties relevant to the model's purpose. For example, modeling the building material in the design process of a civil structure would be reduced to mechanical properties.

When modeling civil structures, various models from different disciplines exist, covering different and overlapping properties of the original. Combining these models with data from sensors and other information sources about the civil structure and its surrounding context is essential to monitor the smart civil structure, analyze its properties, and simulate future trends. Software systems realizing this integration are digital twins, capable of sending contextual information and control commands to the actual system. In our understanding, a *digital twin* is an active software system. It consists of

> "a set of *models* of the system and a set of *digital shadows*, both of which are purposefully updated on a regular basis, provides a set of *services* to use both purposefully with respect to the original system, and can send information about the environment and control commands to the original system."(originally published in (Bibow et al., 2020) but updated after a Dagstuhl seminar on DTs[1])

The set of models are the disciplinary models we are describing in the following section and which need an

[1]Dagstuhl Seminar "Model-Driven Engineering of Digital Twins", `https://www.dagstuhl.de/22362`

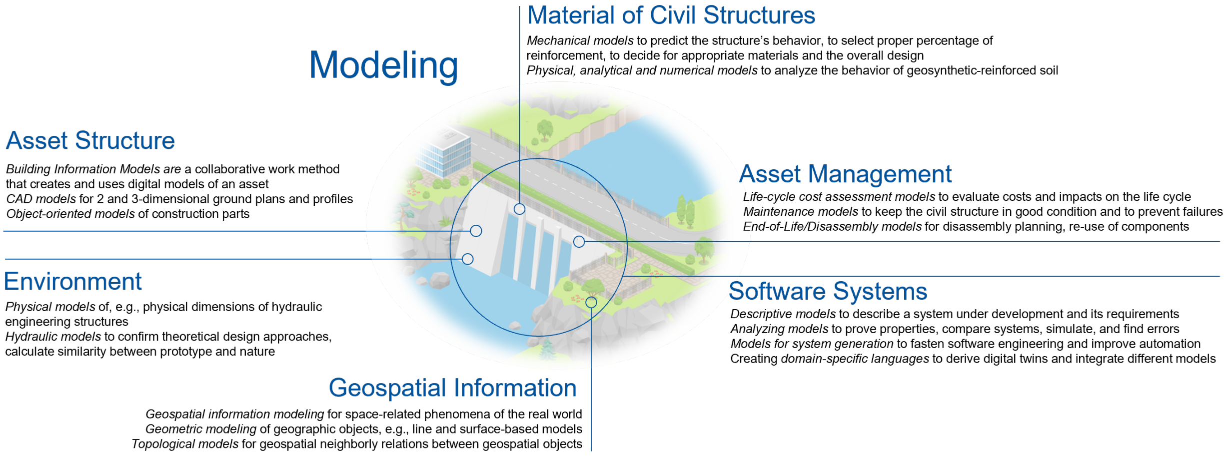

Figure 2: Different perspectives on the same civil structure

additional description of their interrelationships. A *digital shadow* is “a set of contextual data traces and/or their aggregation and abstraction collected concerning a system for a specific purpose with respect to the original system” (Becker et al., 2021). Following this definition, a digital shadow is a passive set of data that is an information source about the civil structures' state and historic states. A digital twin for civil structures enables us to define services that use model information and digital shadows for different purposes such as optimization, inconsistency detection (Brockhoff et al., 2021), simulation, or sustainable operation to support the different stakeholders.

There exist several approaches to use digital twins for civil infrastructures, e.g., (Zandi et al., 2019; Callcut et al., 2021; Gürdür Broo et al., 2022; Pregnolato et al., 2022; Wang et al., 2022; Conde López et al., 2021). Liu et al. (2023) shows an overview of used technologies to create digital twins for civil structures. Some approaches are already connecting models and data from different research disciplines, e.g., Chang-Su Shim and Jeon (2019) use a 3D geometry model (BIM-based parametric models), as well as analysis models to describe bridges and provide services for bridge maintenance and damage analysis. To handle the information, they integrate data from inventory systems, attributes, as well as historical information, e.g., about repairs. Alibrandi (2022) is creating a risk-informed DT using data-driven methods for multicriteria decision support for sustainable and resilient design in the early stage, or management under uncertainty. Park and You (2023) use GIS-based geospatial models together with hydraulic and hydrological simulation models to support decision-making for flood response and water resource management.

What can be seen in the literature is that approaches integrating Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) within digital twins are largely missing. As requirements for sustainability assessments are continuously growing, one can see growing research on LCC and LCA, e.g., of dams (Liu et al., 2013; Zhang et al., 2015; Mostafaei et al., 2023; Hadj Sadok et al., 2022). However, LCC and LCA approaches are rarely part of digital twins, even though they often require similar or the same data and models and would benefit from this connection.

Research on digital twins is massively growing (Dalibor et al., 2022b). However, aspects where we would still see the need for more research are (1) more multidisciplinary and holistic views combining different perspectives and reusing models and data, (2) to use models created in the design and engineering phase of a civil structure during the usage phase of the civil structure, and (3) digital twins covering the whole life cycle of a civil structure up to its end-of-life and reuse of components including regular updates from reality based on changes.

3. Models of intelligent civil infrastructural systems from different research perspectives

Within Figure 2, we give an overview of different perspectives that come together when designing, building, and operating a smart civil structure. The following subsections describe the used models for the building structure, geospatial information, used materials, the environment, building management, and software systems for smart civil structures in detail.

3.1. *Modeling the Building Structure*

With the digital transformation, novel digital business processes and methods are introduced into different industry sectors. The upcoming method in the construction industry is BIM. BIM is defined by BMVI (2015) as

> "... a collaborative work method that creates and uses digital models of an asset as a basis for the consistent generation and management of information and data relevant to the asset's life cycle as well as for the sharing or passing on of such information and data between the participants for further processing by way of transparent communication."

The concept of holistic, digital modeling of construction-related data was formulated in 1997 (e.g., van Nederveen and Tolman, 1992), and in 2007, the US National Institute of Building Sciences (NIBS) introduced BIM as a product to facilitate collaborative processes and described it as a facility life cycle requirement. Currently, NIBS defines BIM as "a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward" (NIBS, 2015).

3.1.1. *Computer-aided design (CAD) and BIM*

BIM method and its models originated from CAD technology. Thus, its primal purpose was the modeling of two-dimensional ground plans and profiles during the design and planning phase. This mainly includes the use of geometric primitives such as points, lines, and polygons, but also graphical presentation details. If labels are applied, these are often placed for presentation in the plans without linking them to objects. Various CAD software offers the derivation of 3D graphical models.

3.1.2. *Object-oriented modeling of construction parts*

However, with BIM although still mainly addressing design and planning of constructions, the aim shifts towards modeling holistic construction parts enhanced also with non-geometric data. Thus, construction parts are modeled in an object-oriented way. The information carrier is the construction part (e.g., wall, door, beam) itself with different characteristics, including geometric and non-geometric attributes, as well as semantics and relations such as membership to other construction parts. Geometric attributes represent the three-dimensional geometry, whereas the non-geometric attributes cover physical, functional, or technical information (Fig 3).

In BIM the modeling perspective is mainly inherited by CAD and used as a tool for planning. Here, geometries are usually defined as constructed solid geometry (CSG), which is an implicit method to construct complex surfaces or objects using Boolean operators to combine simple volumetric parameterized bodies such as cylinders or cones (Herle et al., 2020). The position and orientation of the constructed geometries are specified in the local Cartesian coordinate system (Witte et al., 2020).

3.1.3. *Aspect models in BIM*

BIM models are often a composite of different partial models (aspect models) with different perspectives on the same construction. Like the construction of a building is accomplished by multiple players from the AECO industry (architecture, engineering, construction and operation), a complete BIM model consists of multiple discipline (or aspect) views (Törmä, 2013). For example, architectural models represent usage and aesthetics, structural models describe the construction and stability, and the technical building system (TBS) model covers heating, ventilation, and air conditioning (HVAC) equipment. Since every discipline model is a partial representation of the physical object, interrelation between the models is mandatory. Aspect models overlap with other aspect models, particularly spatially (e.g., walls, entities, equipment). Inconsistencies between the models must be avoided since otherwise they may become quite costly in subsequent phases of the life cycle. BIM tools support, e.g., (spatial) collision detection to avoid inner-model or between-models inconsistencies.

3.1.4. *Additional construction related data in BIM*

Since currently BIM is mainly used in the design, planning, and construction phase of a building, additional data can be managed within the BIM model. Like the definition of BMVI (2015) suggests, BIM models are not solely digital shadows of the construction but also manage construction-related data during the asset's life cycle. Supplemental models for time management, cost planning or documentation can be linked to entire or partial BIM or models of single construction parts.

3.2. *Models from the Geospatial Information Perspective*

ISO 19101 (ISO/TC 211, 2014) defines geographic information as "information concerning phenomena implicitly or explicitly associated with a location relative to the Earth". Huisman and de By (2009) define a geographic phenomenon as a manifestation of an entity or

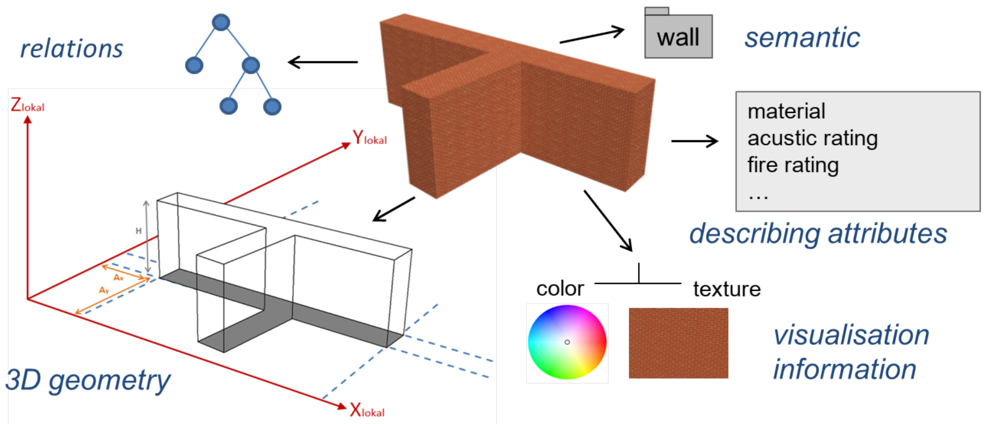

Figure 3: Semantic data model of a wall including attributes and relations ((Witte et al., 2020))

process, which (1) can be *named* or *described*, (2) can be georeferenced and (3) can be assigned a *time (interval)* at which it is/was present. Thus, the modeling process of geospatial information includes multidimensional data to characterize real-world objects. Herle et al. (2020) defines the term geospatial information modelling (GIM) in the style of the BIM notion as follows:

> "Geospatial information modelling (GIM) denotes the digital modeling method of space-related phenomena of the real world. It is characterized by multidimensional descriptions of geospatial features by location and orientation in spatial reference system (SRS), raster/vector geometry and topology, attribute data, and time. Thus, GIM is used as a digital documentation of real-world states and can be applied to a variety of spatially related questions."

Geospatial information and phenomena can be categorized into geographic fields or features based on their real-world appearance. Discrete or continuous *geographic fields* describe geographic information or phenomena that can be determined for every location on the earth's surface. This includes, e.g., air temperature or land cover classes. Typically, geographic field data is stored as raster data, with each cell storing one phenomena value. *Geographic features* (also called geographic object or entity) on the other hand are well-distinguished, discrete, and bounded entities with undetermined space between them (Huisman and de By, 2009). Geometrically they are mostly described by vector models. Digital representations of real-world objects like buildings utilize geographic features. geographic information system (GIS) as a tool supports the input, management, analysis & presentation (IMAP) principle of geospatial data.

3.2.1. Geometric Modeling of Geographic Objects

Historically speaking, in GIM geometric models orientate on graphical visualization for mapping geographic information. Therefore, geometric models in GIM are often line and surface-based models such as the DIME (Corbett, 1979) or the TIGER (Marx, 1986) of the US Bureau of the Census.

In a vector model, the locations of geographic features are described by geometric base forms such as points, lines, polylines, or polygons in a two- or three-dimensional Euclidean space. A building for instance can be modeled geometrically by a polygon representing the groundplan. The edges of the polygon are specified by 2D coordinates in a SRS. With the introduction of city models, 3D bodies (volumes) were introduced into geospatial modeling (Witte et al., 2020).

ISO 19107 (spatial schema) (ISO/TC 211, 2019) specifies the geometrical characteristics of geospatial features. The base geometry class has a link to SRSs and is specialized in primitive, complex, and aggregated geometries. A primitive geometry can be of type point, curve, surface, or solid as specified above. Multiple non-intersecting primitive geometries with a common SRS can be bundled into a complex geometry. Aggregated geometries are loose collections of geometry objects. The Simple Feature Model (SFM) originated by the OGC (Herring, 2011) and taken over by ISO 19125 (ISO/TC 211, 2004) simplifies the spatial schema to 2D (Fig 4). The simple feature geometries consist of vertices specified by coordinates (x, y) interconnected with straight lines.

The geometric modeling approaches of GIM and BIM are similar, but the modeling of construction parts has some major distinctions. This concerns mainly the defini-

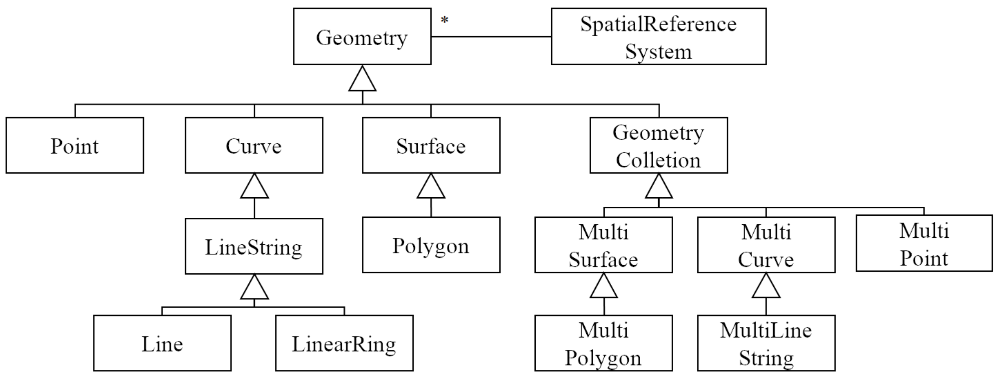

Figure 4: Geometries in the Simple Feature Model (adapted from (project, 2022))

tion of geometric attributes since BIM aims at modeling a construction or parts of it in a detailed view while GIM deals with modeling geospatial features of the real world on a small scale. Hence, GIM uses surface-based models, in 3D such as in CityGML the so-called boundary representation (B-Rep) (Gröger et al., 2012). BIM utilizes mainly the CSG approach. Additionally, in GIM SRSs are used for positioning and orientation rather than the local Cartesian coordinate systems in BIM.

3.2.2. Topological Modeling

The topology describes the geospatial neighborly relations between geospatial objects but independent of the geometry. For example, on a Paris metro map, stations are displayed in relation to each other, regardless of their actual positions or shapes, as these details are irrelevant to the use case. The topological model for GIM is also defined in ISO 19107 (ISO/TC 211, 2019). A base topological object is subdivided into topological primitives and topological complexes. Primitives include nodes, edges, faces, and solids which often have also a geometrical representation. A topological complex is usually created and represented by a geometrical complex. Graph theory with the concepts of nodes and edges is the basis of topological modeling (Bill, 2016).

3.2.3. Attributive Modeling

Attributive (or thematic) modeling covers describing, editing, and storing thematic issues associated with a geospatial object. In GIM, this is performed by thematic layers, classes, objects, or hierarchies. The *layers* principle separates geometry and graphical data from different thematic issues by using several layers. The common denominator is the spatial reference of the data. Several thematically dedicated layers overlay to form the complete map display. Using a *classes and objects* model, geospatial features are grouped by common characteristics. Classes describe the common attributes while objects are derived manifestations of classes. The notion of "geospatial" objects adds a spatial reference, e.g., in the form of a shape and position for a ground plan, to the class building and its objects. With this geospatial classes and objects model, GIS can be used to process geospatial and/or attributive requests.

3.2.4. Temporal Modeling

In temporal modeling, temporal objects are added to geospatial features, formalized by ISO 19108 (ISO/TC 211, 2002). This might be an instant in time, a time period or a complex construct. There are two approaches, SNAP and SPAN, for introducing time Grenon and Smith (2004). The SNAP(shot) approach describes states of a geospatial feature (snapshots) at specific points in time. The SPAN approach describes the ontology of what happens (SPANning a period of time). If an attribute of a geospatial feature changes, this change is stored together with a timestamp. According to Bill (2016) the SPAN approach has a greater storage efficiency, whilst the SNAP ontology allows simpler queries for specific snapshots.

3.3. Modeling Smart Materials of Civil Structures

Civil structures are built from various (smart) materials such as concrete, soil, steel reinforcement, and geosynthetic reinforcement. Their specific characteristics are modeled to design a civil structure properly. Within this section, we discuss the modeling of geosynthetic-reinforced soil (GRS) in detail which is prominent for structures like dikes, retaining walls (Jewell, 1996; Koerner, 2012b), embankments (Helwany, 2003; Bathurst et al., 2003; Shen et al., 2020), and foundation pads (Adams and Collin, 1997; Demir et al., 2013). However, other material engineering perspectives use domain-specific modeling methods. Today, in civil structures GRS has become a standard to reinforce, protect from erosion, separate different soil types, filter or drain (Koerner, 2012a). Compared to conventional construction methods, geosynthetic-reinforced structures are often more economical and have a more environmentally friendly life cycle assessment (Damians et al., 2017; Fifer Bizjak and Lenart, 2018).

Geogrids (Figure 5), an example of geosynthetics, are prominent for the reinforcement of civil structures. They consist of fibers and are mechanically modeled on different levels (Figure 6): to predict the structure's behavior, select the proper percentage of reinforcement, decide on appropriate materials, and the overall design of a textile. These modeling levels include models for filaments/fibers, filament/fiber bundles (yarn or roving), and textiles (processed yarns/rovings), as well as for the interface between the textile and soil particles, soil body units or the complete soil-textile structure. Usually, the models are validated by implementing geosynthetics into a physical model, e.g., a scaled hydraulic model (prototype), as described in Section 3.4.

Geosynthetics also offer a chance for carrying massive sensor networks to digitize civil structures to, e.g., accurately monitor their health. For monitoring strain in textile-reinforced components, optical fibers with fiber bragg grids are commonly used (Bunge et al., 2017). For sensing humidity, carbon fibers can be used (Schwab et al., 2021; Perry et al., 2021).

3.3.1. Modeling of GRS from a Textile Perspective

The modeling of textiles is derived from the field of fiber-reinforced plastics. Dry fibers and textiles can be used in any kind of surrounding matrix system, like polymers, soil, or concrete, and thus are similarly relevant for smart civil structures (Hesseler et al., 2021). There are three typical scales in textile modeling and simulation:

- In **micro scale** simulations, the interaction between filaments/fibers and other components is investigated. Models at the micro-scale are trying to evaluate the properties of rovings (a long and narrow bundle of fiber) (Durville, 2005; Miao et al., 2008; Zhou et al., 2004). E.g., filaments/fibers within a roving are often approximated as perfectly straight and parallel even though this is not true for real rovings (Durville, 2010; Zhou et al., 2004; Stapleton et al., 2018). Therefore, some approaches consider entanglement in fibers (Sherburn, 2007; Stapleton et al., 2017).

- In **meso scale** simulations, interactions between yarns/rovings and other components are investigated, utilizing the results of the micro-scale simulations to define roving properties. Rovings are represented with continuum elements, which means no filaments are modeled. The behavior of the thousands of filaments within a roving is represented through specific material properties of the roving.

- In **macro scale** simulations, we focus on the interaction between textiles and other components. Macro scale models of dry textiles usually investigate the textile forming (draping) behavior to reduce draping defects like gaps, folds, loops, or ondulation. The dominant deformation mechanism during draping is the shearing of the textile, which is a complex, nonlinear behavior (Boisse et al., 2011; Pierce et al.).

The textiles in the presented simulations schemes and methods on different scales are often dense textiles with a relatively high areal weight. These schemes and methods are adaptable for textiles in civil structures (Hesseler et al., 2021).

3.3.2. Modeling of GRS from a Geo-Mechanical Perspective

The design of GRS involves a complex interaction behavior due to the force transfer at the soil-geosynthetic interface (Ezzein and Bathurst, 2014; Morsy et al., 2019; Jewell, 1996). The performance of GRS is comprised of the material properties of the reinforcement, the adjacent soil, and the interaction between both components. The modeling of geogrid-soil interaction covers interaction modes, model types, and scales. The behavior of GRS can be examined from a micro, meso, and macro perspective, however, the scales are interconnected.

- On the **micro-scale**, the single soil particles interact with the geogrid tensile elements. The interaction behavior depends on soil properties, e.g., density, grain size and shape, moisture, and shear strength (Lopes and Ladeira, 1996; Lashkari and Jamali, 2021; Liu et al., 2021) and on characteristics of the geogrid, e.g., geometry, type, stiffness, and roughness (Palmeria and Milligan, 1989; Lopes and Lopes, 1999; Moraci and Recalcati, 2006; Al-Barqawi et al., 2021).

- On the **meso-scale**, the global stress-strain behavior of the geogrid-reinforced soil body is idealized as a continuum with enhanced strength or confining stress of the GRS unit. Also, prevailing boundary conditions are considered, e.g., stress level, load characteristics, temperature, specimen size, and testing equipment (Razzazan et al., 2018; Sun and Han, 2019; Chao and Fowmes, 2021).

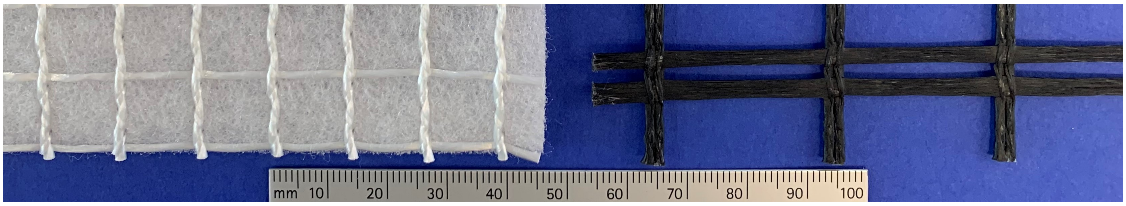

Figure 5: Left: High-modulus reinforcement with an integrated nonwoven component for the reinforcing, separating, and filtering function made of polyester and polypropylene. Right: Geogrid for soil reinforcement made of high-modulus polyester. Source: ITA

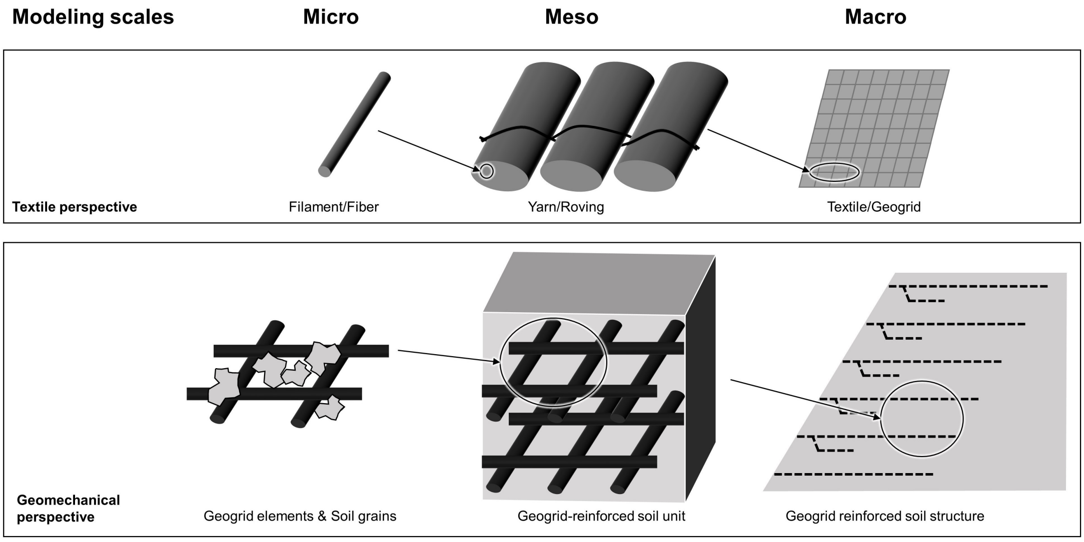

Figure 6: Scales for modeling textiles in soil

- On the **macro-scale**, GRS is considered as a structure interacting with the subsoil, e.g. in slopes, walls, abutments, or foundation pads.

To analyze the behavior of GRS, physical, analytical, and numerical models can be used. Physical models are performed as a standardized index to quantify the interface efficiency and the behavior of reinforced structures. In direct shear tests, the geogrid-soil interface is subjected to a shear movement representing the mode of sliding. Contrary, in pullout tests, the geogrid is actively pulled out of a confined fill. Different scales (full- or small-scale) and gravity conditions (1-g or n-g) are used to ensure the transferability of the experimental results.

3.4. *Modeling the Environment of Intelligent Civil Infrastructural Systems*

The environment of smart civil engineering structures is usually a combination of soil, air, or water. Depending on the specific environment, this requires expertise from different engineering disciplines. Structures in contact with water, such as dams, require knowledge of hydraulic engineering. In hydraulic engineering, models are used to understand or assess flow-associated processes, applications, or protection measures in a well-controllable environment. Such models typically focus on water and encompass investigations of natural processes (rivers, marine environments, and groundwater) and hydraulic engineering structures (weirs and hydropower plants) (Briggs). A model in hydraulics is defined as "a physical or mathematical simulation of a ‘prototype’, or field-size situation" (Novak et al., 2010). In this context, a model is considered as a system that results in output parameters, e.g., flow rates or pressures, depending on given input parameters, such as geometry and boundary conditions. The terms ‘model’, ‘hydraulic modeling’, and ‘models in hydraulic engineering’ include physical and mathematical models and are clearly distinguished from the term ‘hydraulic model’, which defines a physical scale model of a hydraulic system. According to (Stachowiak, 1973), a hydraulic model is a dynamic-mechanical model. Figure 7 depicts a classification of the several terms of modeling based on (Novak et al., 2010).

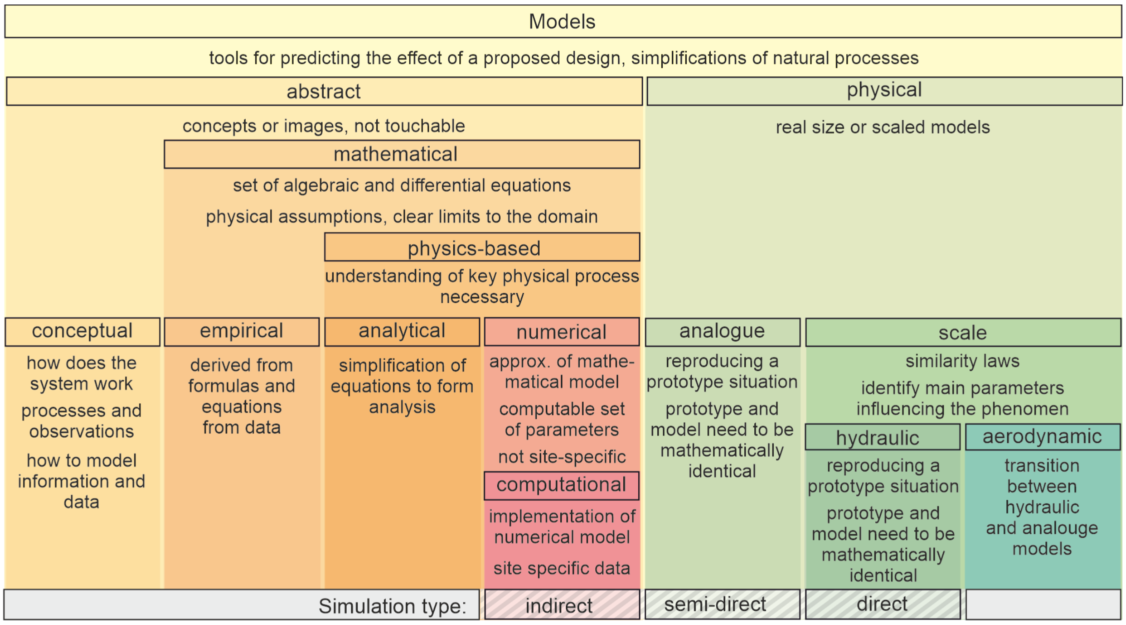

Figure 7: Classification of models in hydraulic engineering (based on (Novak et al., 2010)), which has analogies in the other domains.

Today, hydraulic models are applied to confirm theoretical design approaches (Aigner et al., 2015) when there is a lack of theoretical solutions, and to determine empirical coefficients that serve as input parameters to mathematical modeling. The best and most cost-effective solutions are often achieved by combining physical and mathematical modeling (Novak et al., 2010). Planning a scaled hydraulic model and interpreting the raw data sufficiently, requires (i) dimensional analysis to determine dependent and independent variables (Kobus, 1974) and (ii) scaling laws to transfer the results to the nature scale (Novak et al., 2010). The mechanical similarity between prototype and nature, intended for hydrodynamic experiments, is composed of geometric, kinematic, and dynamic similarity (DeVries, 1982). A model is geometrically similar when the ratio of all lengths (the scale number) in nature and model is constant. Water flows are affected by mass forces, inertial forces, frictional forces, capillary forces, and elasticity forces. The full mechanical similarity is exclusively reached by a scale ratio of 1:1. This is usually not feasible due to space and cost constraints. Therefore, depending on the problem, only the two dominant types of forces are considered and the remaining forces are neglected (respectively distorted) in downscaled models, resulting in model laws (e.g., Froude or Reynold laws).

3.5. Models for Asset Management

From the business management perspective, especially models related to life cycle cost, environmental assessment, and building management are relevant. While life cycle costing models evaluate expenditures, life cycle assessment models determine the environmental impacts of a building over its life cycle. Maintenance models keep the smart civil structure in good condition and prevent failures, while end-of-life models tackle disassembly planning, and re-use and recycling of components and materials.

3.5.1. Life Cycle Costing (LCC)

LCC is the act of compiling all costs related to a product/asset containing all expenses from the design to end-of-life. Herein, decision makers gain an overview of the full budget, including all expenses and revenues, and thus can compare product/design options. During the past years, numerous researchers have carried out LCC on civil structures. Many of them evaluated the lifetime costs of civil structures such as pavements (Huang et al., 2009, 2021), bridges (Tao et al., 2021), residential buildings (Conci et al., 2019; Rodrigues et al., 2018a), railways (Vandoorne and Gräbe, 2018), and also construction industry (AbouHamad and Abu-Hamd, 2019). Methods like mathematical models (Xin et al., 2021), decision-making tools (Tao et al., 2021; Rodrigues et al., 2018b), programming techniques (Umer et al., 2017), and simulations (Vandoorne and Gräbe, 2018) were used to assess and optimize the budget allocated to the project. Uncertainties (future prices, lifetime, maintenance effort) are a big challenge, especially for products with a long lifetime such as civil structures. Minimal expected costs can be determined based on the risks of loss (Wu et al., 2006). From a decision-making perspective, long-term decisions bear challenges as planning horizon and operational horizon often differ (Breuer et al., 2013).

3.5.2. *Life Cycle Assessment (LCA)*

LCA is a methodology for evaluating environmental effects concerning all the phases of a product's life cycle. While LCA is often applied to products of rather short lifetime (e.g., consumer goods, packaging), there is also a multitude of literature analyzing environmental impacts for construction structures such as bridges (Tao et al., 2021; Georgios et al., 2020), streets (Huang et al., 2009, 2021), constructions (AbouHamad and Abu-Hamd, 2019). Often, the life cycle phases, e.g., the material demand during construction or the energy demand during usage, are combined in an analytical model using specific LCA software like OpenLCA (Pamu et al., 2022), Gabi and SimaPro (Herrmann and Moltesen, 2015) for Europe or ATHENA (Srinivasan et al., 2014) in the US and Canada (Islam et al., 2015). Then, this information on direct material and energy use is merged with information on the environmental impact resulting from the pre-chain processes for producing the required materials and energy carriers based on databases like ecoinvent (Pascual-González et al., 2016). While this is mostly done as a stand-alone system, implicitly retrieving highly aggregated information, e.g., on material utilization (Bill-of-Quantity, Bill-of-Materials), some frameworks retrieve the information from BIM (Lu et al., 2021).

3.5.3. *Maintenance Models*

A maintenance policy is required during the utilization phase of the civil structure. Maintenance optimization aims at reducing the operation and maintenance expenditures while assuring required safety standards. Preventive maintenance (PM) applies maintenance measures on a regular (fixed) schedule to keep the civil structure in good condition and to prevent any expensive unexpected downtime before a problem occurs (Han et al., 2021; Bakhtiary et al., 2021). Predictive maintenance (PdM) on the other hand is based on information on the current condition and utilization of an asset/structure and maintenance measures are applied if needed (Lopes Gerum et al., 2019). PM as well as PdM are applied to diverse types of civil structures, such as bridges (Morcous and Lounis, 2005), tunnels (Ishida et al., 2018) and pavements (Han et al., 2021). In the case of available sensor data, predictive maintenance is superior to corrective or preventive maintenance since it enables deriving reliable life expectancy forecasts based on constant condition monitoring using statistical and machine learning methods (Kovalev et al., 2018). Predictive maintenance can be fully automated or enriched by expert opinions (e.g., (Flores-Colen et al., 2010; Klein et al., 2021)).

3.5.4. *End-of-Life/Disassembly models*

The transformation towards a circular economy requires measures for lifetime extension, re-use of components, and circularity of materials. This requires a design for disassembly (Ekanayake and Ofori, 2004) to support the construction of civil structures that enable selective disassembly and recycling of separated materials (Oyedele et al., 2014). Disassembly is a reversal procedure in which a structure is disjointed into its components and/or subassemblies and materials (Tleuken et al., 2022). Disassembly planning and adaptive reuse of buildings is based on disassembly graphs (Sanchez et al., 2018). BIM software lacks the ability to explicitly regard for end-of-life evaluations during the design stage (Lukman et al., 2019). However, first approaches use the information of BIM to evaluate the feasibility for disassembly (Akinade et al., 2015; S. et al., 2021) or to plan for disassembly (Cheng and Ma, 2013).

3.6. *Modeling Software Systems for Smart Civil Structures*

From a software engineering perspective (Hölldobler et al., 2019), models can be used with different purposes in the development process of software artifacts for civil structures as well as for interrelations between different systems and models:

Describing Models are used to describe a system under consideration or development. Thereby the models can range from very formal, mathematical models following a defined syntax (Broy and Stølen, 2001) up to informal drawings. These models can have both, documentary characters as well as specifying characters. More informal models can be used to facilitate communication between different stakeholders or within the development team. More formal models, on the other hand, can also serve as a requirements description and specify which properties the system to be developed must fulfill.

Analyzing If the models are formal and follow clearly defined semantics (Harel and Rumpe, 2004), they can also be used to analyze a system. These analyses can, for example, prove the properties of the system and thus demonstrate the functional safety of a system (Kausch et al., 2021). Models can also be compared with each other and thus used to analyze an evolving system or product line of systems. Models can be compared both structurally and semantically (Maoz et al., 2011b,a). A special form of analysis is in particular the simulation of a system.

Synthesizing (Generating) When models are created in a machine-readable form, they can be used to automatically synthesize or generate (parts of) a system. Such generation can relieve developers of repetitive work such as serializing data to send it via a network. The higher level of abstraction of models compared to general-purpose programming languages enables developers to think more about the business logic and less about the technical implementation. Although not identical, there is a considerable degree of similarity to the field of low-code development (Di Ruscio et al., 2022; Dalibor et al., 2022a).

The various purposes of modeling in software engineering imply that models can be used at a wide variety of times during the development of a digital twin for intelligent civil infrastructure systems. Models can be created before the development of the actual system begins to specify the requirements for the DT. At design time, models can describe, verify, and partially automate the generation of the digital twin to be developed, and analyze the sustainability of the planned system (Gramelsberger et al., 2023). Models can be used to connect existing systems, e.g., Cyber-Physical Systems (CPSs) with information systems (Kirchhof et al., 2020), or a DT with IoT systems (Kirchhof et al., 2021, 2022). At runtime of the DT, models can be used, for example, to localize errors, or to enforce rules (Szvetits and Zdun, 2016). At runtime, annotations or additional models can be used to combine models from different perspectives within a DT (see Figure 8), connect the models with sensor data from smart civil structures, and integrate data visualizations within models, e.g., models for mechanical functions (Drave et al., 2020; Michael et al., 2022) of hydraulic systems related to a dam or geospatial models of the environment. Even after the operative runtime has ended, models can still be used to retrospectively analyze errors that occurred during its runtime (Kirchhof et al., 2021; Babaei and Dingel, 2021).

During the software development process, the models are not necessarily only relevant for developers. Due to their often high level of abstraction, models can be important communication tools while talking about parts of the system with non-technically trained stakeholders. In particular, as software becomes more complex and specialized, it can be a problem that the software developers are not experts in the domain of the software being developed. In other words, there can be a “wide conceptual gap between the problem and the implementation domains” (France and Rumpe, 2007). For example, software developers working in the civil engineering domain will rarely have had similar education and training as an architect, civil engineer, or hydraulic engineer. To ensure that the software nevertheless meets the requirements of its users, it is therefore desirable to increasingly integrate domain experts into the development process. The high level of abstraction of models can be leveraged to let domain experts specify parts of the system

To achieve this, Domain-Specific Language (DSL) can be used. In contrast to general-purpose programming languages, DSLs explicitly do not have the goal of describing all possible problems and solutions. Instead, DSLs can be tailored to a very specific use case and allow domain experts to get involved in the development process through a syntax adapted to the domain. For example, a DSL intended for environmental impact assessment of building new dikes might include legal, geographical, and environmental engineering terms to fit the needs of For the development of such DSLs (Combemale et al., 2016), language workbenches such as Xtext (Bettini, 2016), JetBrains MPS (JetBrains), or MontiCore (Hölldobler et al., 2021) are available. With the help of such language workbenches, (often textual) DSLs can be defined via grammars and associated context conditions. The language workbenches then automatically generate the tools necessary to read in models of the DSL. Downstream code generators can then process the information to automatically create (parts of) a system, e.g., digital twins and digital twin cockpits (Michael et al., 2022; Dalibor et al., 2020; Bano et al., 2022) and provide an integrated view for different models, e.g., by using links (Raţiu et al., 2022; Shekhovtsov et al., 2018).

4. A Digital Twin for a Dam: Purpose, Services, Models, Data and Control

A digital twin of a dam, e.g., a concrete wall or an earth structure, can fulfill different **purposes**. These include monitoring and maintenance of dams, decision support in or before a flood event, or the prevention of crises. Dependent on these purposes, a digital twin of a dam has to realize a set of **software services**: Monitoring of the dam structure, analyzing the safety of a dam (Conde López et al., 2021), maintenance, planning (e.g. raising of the water level), flood simulations, load simulations, life cycle costing updates, the coordination

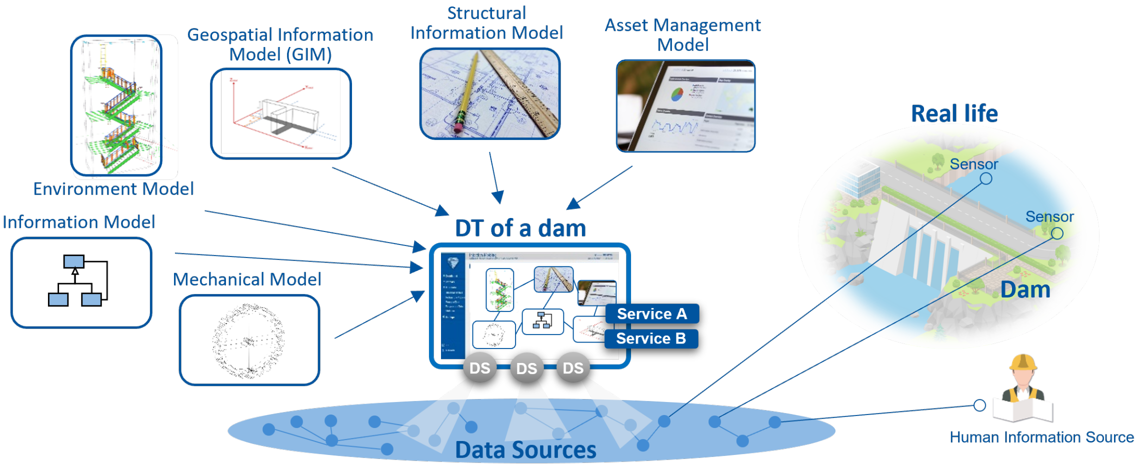

Figure 8: Integrating different modeling perspectives for intelligent civil infrastructural systems in digital twins

of emergency services, or visualization of all this information (Park and You, 2023). These services require both, models and data on the dam.

Used **models** include, e.g., geometric-semantic models (in the large scale BIM, and on the small scale geoinformation models/GIM), physical and numerical models describing its hydraulics, sensor models, water level models, weather models, or agent-based models to describe human-flood-structure interaction. The information in these models can be overlapping, e.g., 3D geoinformation models provide some of the needed parameters to be used for analyzing the dam reservoir in hydrologic models, or the amount of rainfall identified in weather models influences water level models. These models have to be combined with real-time synchronized and historical data to be useful in a digital twin.

The used **data** includes data from measurements, e.g., laser scanning, photos, close and remote sensing of the dam, as well as existing geodata. Another area of data is related to the structure of the dyke (e.g., materials). In general, this includes the status of existing control options, the maximal permissible discharge, spillways, reservoir volume, or target water level in the reservoir. In the digital twin of the earth dam, soil data (e.g., layers, grain sizes of soil types, kf value, information on sealing materials) and settlement behavior are relevant. If one is twinning the dam wall, data about the concrete such as stress/strain behavior, temperature-dependent behavior, weather-related behavior (e.g. corrosion), and aging are of interest. Sensor data is automatically sent to the digital twin, e.g., from strain sensors, moisture sensors, temperature sensors, or pressure sensors. One can detect hydrological and hydraulic data, such as water level data, flow velocities and discharge data, slope, and sediment transport (abrasion, impact). One can add weather data, which counts in principle as hydrological data and is required for water level simulations. The wind velocity and ice are of interest as load cases, as well as the temperature as it affects the structure of the dam. In addition, the digital twin of the dam includes data from the care and maintenance of the structure, e.g., photos, or damage reports.

When it comes to direct **control** of a dam by sending control commands, for both, concrete walls or earth structures, the inspection tunnel is used, e.g., to check if the post-injection for sealing is possible without problems or if the automated seepage water drainage works. In the withdrawal structure, one can control the water withdrawal for various uses. In the bottom outlet, one can control the discharge into the downstream river. Moreover, the spillway can be either controlled or uncontrolled (so with or without gates). For *concrete dams*, e.g., control commands to steer a planned overflow can be sent.

For the different purposes a digital twin of a dam has to fulfill, we need a connection of the information sources and models throughout its lifetime. Having information about the current dam structure and ongoing maintenance can be used for planning predictive maintenance. However, this information is also relevant for updating LCC and LCA models and analysis results from the design of a concrete dam (Liu et al., 2013; Zhang et al., 2015), e.g., as a part of identifying their CO_2 emissions during operational maintenance. Geospatial and geometric models of the dam in connection with sensor models and the concrete sensor data can provide information in

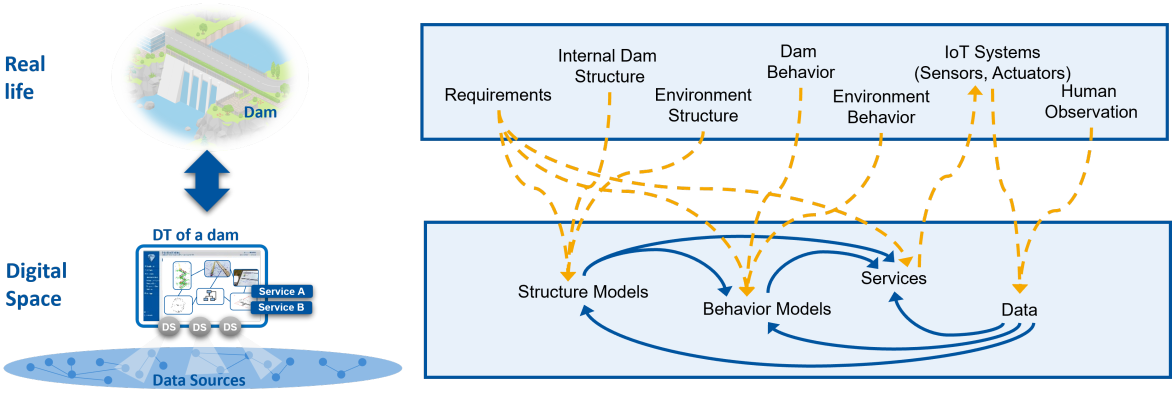

Figure 9: Connections between different real-life components and digital twin components to be considered when co-evolving digital twins with the dam (connections between the real-life dam and the digital twin in yellow, influences of changes within the digital twin in blue)

the event of imminent flooding and make decisions for planned overflows or controlled discharges.

The **co-evolution** of a digital twin with a dam is especially challenging, as dependent on what has changed in real life, one or more artifacts of the digital twin have to change (see Figure 9). To give some examples: Co-evolving requires updates of used models, e.g., we need to recalibrate simulation models of floods based on changes in the geospatial data about the dam taken from real-life measurements. If new sensors are added or old ones are replaced, we have to update the data models as their structure changes and might have to migrate existing data and digital shadows; this update in the data structure triggers changes in other models and services, as we aim to use this data. If additional requirements and purposes occur, e.g., when a new regulation requires providing further analyses or a sustainability assessment requires the calculation of additional metrics, we have to add new software services.

This interweaving information, however, requires new approaches to handle these connections - between different models, between different datasets but also between data and models (Michael et al., 2024) and the establishment of a continuum between design, operation, updates in the physical structure during operation, back to future designs (Combemale et al., 2023). The 7R taxonomy of digital twin evolution (David et al., 2024; David and Bork, 2023) gives some ideas on how to handle, e.g., recollection of data, recalibration of models, remodeling, reconciling, redeployment, reconfiguration, and reuse of digital twin components. However, these ideas have to be further explored with concrete examples of smart civil structures.

5. Challenges and Discussion

The different modeling perspectives for designing, building, and operating civil structures should not be separate models but instead interconnected and integrated via interfaces. When consolidating these different modeling perspectives to be used within a digital twin, we still have to face several challenges such as handling interoperability, combining heterogeneous data and information sources, handling multiple disciplines and their terminologies, and adapting to changing technologies and software stacks.

5.1. Interoperability of models

Interoperability is defined as "the ability of two or more systems to exchange information and to use the information that has been exchanged" (IEEE 610 working group, 1990). As mentioned, interoperability plays an important role in establishing a holistic digital model of sustainable and smart civil structures. Throughout this paper, it becomes evident that a holistic digital representation of a structure requires many disciplines from civil engineering, computer science, mechanical engineering via economics and sociology through to stakeholders of the architecture, engineering, construction and operation (AECO) industry. In digital models for civil structures, interoperation barriers are often an issue of different data sources and modeling approaches. For instance, dikes or other coastal defense structures consist of wide-spreading oblong bodies. Those are often digitally managed, documented, and visualized in dike information systems based on 2D-GIS data. However, a holistic digital representation (DS or DT) of a dike can be best modeled with a 3D model from the BIM domain focusing on single constructions. But here lies an interoperability barrier (c.f. Section 3) since GIM and BIM

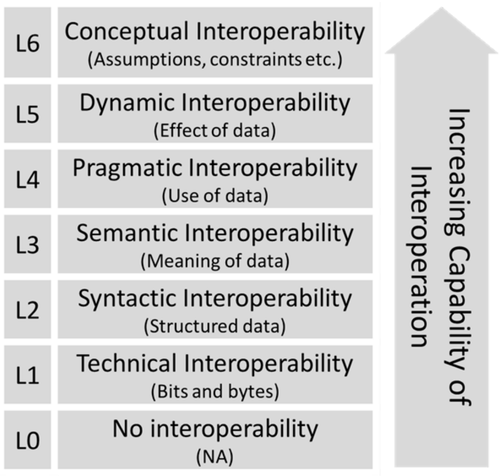

Figure 10: Level of conceptual interoperability model (LCIM) (based on Wang et al. (2009))

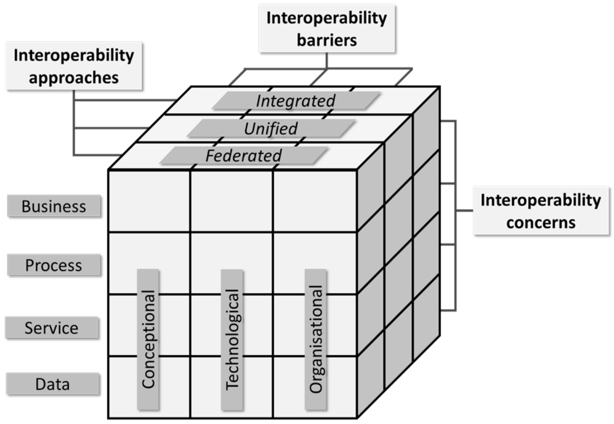

Figure 11: Framework for enterprise interoperability (FEI) (based on ISO/TC 184 (2012))

have different backgrounds and use opposing modeling approaches, e.g., in specifying geometries. Thus, the data from one system cannot be seamlessly integrated into the other.

Using the level of conceptual interoperability model (LCIM) (see Fig. 10), we can describe the technological interoperability between two systems. It consists of seven levels from "no interoperability" (L0) with no connection between systems to "semantic interoperability" (L3) with an agreed set of terms and terminology to, ultimately, "conceptual interoperability" (L6). The question is how to achieve interoperability. In the framework for enterprise interoperability (FEI) interoperability has three dimensions (see Fig. 11). Interoperability barriers can be categorized as conceptual, technological, and organizational. To reduce or remove the barriers, one can use (1) an integrated, (2) a unified, and (3) a federated approach. While the federated approach supports multiple models with mapping rules between them, the integrated and unified approaches establish new complete respectively meta-level models. These approaches can be applied to the different interoperability levels of the LCIM. For instance, if we want to achieve semantic interoperability (L3) between two models, we could apply a federated approach using semantic web technologies such as resource description framework (RDF) and link two or more models. Furthermore, web ontology language (OWL) could be applied to even establish pragmatic interoperability (L4) representing conceptual schemas with rich vocabulary to add semantics and context. Hor et al. (2016) or Vilgertshofer et al. (2017) used this approach to establish interoperability between the GIM and BIM domains.

5.2. Data and Information Sources

Building a monitoring system for sustainable and smart civil structures requires a holistic view of the structure first. Highly accurate digital representations of the structure are needed to, e.g., assess defects, and maintain or overhaul effectively. The overall goal is to establish a digital twin for the structure, which comprises every detail from the real-world structure and is in synchronization with its states. With such a digital representation optimal efficiency, cost-effectiveness, and sustainability throughout the structure's entire life cycle can be achieved. However, before constructing a digital twin or even a digital shadow, the data and information basis of the structure have to be as complete as possible. Additionally, these data sets must fit into the digital model(s) from a conceptual point of view. Therein lies the great challenge, since either the data does not exist, e.g., for old existing structures, it is incomplete or outdated, or—even worse—spread over different digital and non-digital systems such as databases or paper files with various models or file structures. The latter requires digitalization but also ETL (extract, transform, load) methods to achieve data fusion from multiple sources.

A holistic digital representation integrates geometric and semantic information about the surface and subsurface of the structure and sensor data. It has to be constantly synchronized with its physical world pendants. Geometric and semantic information about the structure in the physical world can be obtained by using **reality capturing techniques**. The most common methods to generate as-built information in the industry are laser scanning, digital photogrammetry, or Ground-Penetrating Radar (GPR) (Wahbeh et al., 2020). These data acquisition techniques are still highly manual and time-consuming approaches.

The above-mentioned methods can only capture a part of the key data that are relevant for the life phases of civil structures. Also, technical health parameters are very individual to the structure and can include, for example, stresses, strains, settlements, moisture content, cracking (inside the structure) or flow velocities, water levels, shear stresses, impact forces, and weather conditions (outside the structure). Equally relevant are data for evaluating life cycle costs and environmental impacts. Many methods to collect such data are either expensive to install today or technologically not mature, e.g. no robust sensor technology is available under the challenging conditions (e.g. humidity, long lifetime, need for non-destructive measurement) of civil structures.

5.3. Multidisciplinary Digital Twin Engineering

Developing digital twins for civil structures requires a multidisciplinary approach. In particular, a digital twin can represent not only virtual but also physically existing components of the system (Jiang et al., 2021). Stakeholders in different domains not only use different types of models but also use these models at different times in the life cycle of civil structures and for different purposes. A digital twin of a civil structure must be able to relate these different views to each other and provide added value over strictly viewing each perspective separately. This problem is complicated by the fact that stakeholders from different disciplines not only have different understandings of civil structures but sometimes also share terminologically very similar but semantically different views (a problem occurring in various research domains (Feichtinger et al., 2022)). To avoid misunderstandings in the development of digital twins, a common understanding of the terms used must be created. These different understandings are sometimes reflected in the data formats of the different domains. The same data can be represented differently by different domains. Such different data formats can complicate the integration of data necessary to create a digital twin.

One problem with integrating all these different views is that there is often no single person who understands the system from all perspectives. Each engineering domain always has only partial knowledge of the system. Accordingly, it can also happen that stakeholders from different domains assess different aspects as having different importance for the development of the digital twin. The different weighting of various aspects can also be found in the life cycle. For example, while the construction plans of a civil structure are important before and during the construction phase (prescriptive model), they can become less important over the lifetime of the civil structure if they do not match the as-built state. It may, therefore, be advisable to make the transitions between life cycle phases as smooth as possible. Using the construction plan as an example, we need to continuously update the construction plan within the digital twin during construction, to have an accurate model that corresponds to the actual state and not to a (possibly unachieved) target state in later life cycle phases. Transferring a digital twin from one civil structure to another one will require adjustments. Therefore, a systematic (engineering) process is needed to develop digital twins.

5.4. Adapting to Changing Technologies and Software Stacks

A particular challenge in the development of software for buildings and civil structures is that software evolves usually much faster than civil structures. While civil structures often last for many decades, software and computer hardware that is 20 years old are indisputably obsolete from today's perspective. The problem of software obsolescence extends to many perspectives:

Network Technologies Network technologies are rarely useful for more than a few years. While the Internet was still in its infancy 20 years ago, smartphones today stream videos in 4K resolution over cellular networks. If a network is dependent on communication elements that are not provided by the operator of the civil structure itself, e.g., the radio tower of a cellular provider, these technologies inevitably become obsolete as soon as the corresponding components are no longer provided. A prominent example of this is the shutdown of the 3G network. All devices that are not technically capable of using 4G instead were inevitably affected by this.

Security Even if a network can still technically be used, serious security vulnerabilities can arise from outdated protocols. Thus, protocols are usually no longer accepted by communication partners after a grace period. An example of this is the disabling of SSL/TLS 1.0 and 1.1 in 2021. If a server uses only these outdated protocols, many browsers consider it to be too insecure today.

Data (bases) and Data Formats Civil structures can be much more long-lived than data and especially data formats. For example, MySQL, today one of the most widely used databases, was introduced only in the mid-90s and is, thus, less than 30 years old. There is no guarantee that the data (base) formats that will be used in 30 years already exist today. To keep the data usable, it may be necessary to migrate data from an old format to a new one. Especially in the case of data formats created specifically for a civil structure, this means that there are high requirements for documentation and possibly meta-data. Such documentation and meta-data can enable developers other than the original developers of a system to transfer the data into a new format without the need for time-consuming (and possibly semantically erroneous) reverse engineering.

Operating Systems Even with widely-used operating systems like Ubuntu, Long-Term Support (LTS) typically covers a period of about 5 years, which is well below the lifespan of civil structures. The consequence of using an outdated operating system and the unavailability of newer software packages is that attack vectors resulting from vulnerabilities are not closed by updates.

Software Dependencies There is no guarantee that their respective maintainers will maintain software packages forever. With the change to newer operating system versions or similar, it can happen that a previously used software dependency can no longer be used.

Spare Parts Hardware will not be provided forever by the manufacturers. If hardware components used by and within civil structures, e.g., sensors or network connectors, break, there is no guarantee that replacements can be easily provided.

Since software developers cannot predict the future, it is not possible to write software today that is compatible with software that will be invented and common in the years or decades to come. Therefore, it is essential for software development in this scenario to design the software in such a modular and maintainable way that individual system components can be replaced in the future with the least possible effort.

It should not be neglected that changing technology stacks often include a social component. If the software changes, employees must be trained in how to use the changed software. In particular, this also means lifelong learning of new technologies, languages, and APIs for software developers.

6. Conclusion and Research Agenda

Developing digital twins of civil structures is a complex aim for research requiring that we solve various challenges:

1. Civil structures have long durability compared to software systems, e.g., bridges about 50 years and dikes about 100 years in comparison to software systems which exist for 10 years on average.

2. We have to integrate multidisciplinary views, terms, and concepts that manifest themselves in models using different modeling languages.

3. Our models cover different phases of the civil structure life cycle and are partly overlapping.

4. The models are to a large extent independent of each other and cannot be integrated straightforwardly.

5. Stakeholders can vary widely in size, from single-person operations to multi-national corporations, and require correspondingly different digitization strategies.

6. Data may be missing and is not necessarily available in digital form or is only available in non-integrated scattered form.

However, an integrated perspective within digital twins is needed to tackle global challenges such as sustainability assessment and risk management.

Sustainability. The design, construction, and operation of a civil structure impact (environmental, economic, and social) sustainability and an integrated environmental assessment is required as early as the design phase. Automatically integrating and continuously updating models from the various disciplines involved along the life cycle is key to the successful and sustainable operation of civil structures.

Risk Management. Risk management and protection of security considerations are of utmost importance to reduce losses due to natural catastrophes. One measure to decrease the risk of failure is utilizing sensors to allow for continuous monitoring during the operation phase of the civil structures. Despite the high demands, sensors for continuous monitoring were so far deployed in only a very small number of structures. Installing sensors in civil infrastructures requires that their long-term value be considered more valuable than the increased short-term construction cost. Merging models from different disciplines to aggregate information and provide more meaningful insights could lead to increased safety, a higher lifetime of the structure, and a direct cost reduction during operation.

Research Agenda. A multidisciplinary approach can integrate these disciplinary views from heterogeneous models throughout the life cycle of a civil structure within digital twins. We suggest the following steps to reach this goal:

1. Development of robust and economic structural health monitoring systems for civil structures: by this, structural and design models can be evaluated over the complete lifetime. In the long term, this will lead to improved design guidelines and higher resource efficiency.

2. Establish model interoperability: Models can have overlaps, which have to be detected in an automated way. This requires building bridges between different terminologies of the participating domains and their modeling languages.

3. Develop green-field digital twin construction methods for planned civil structures: This method is required to cover all parts of the construction methods and to know which models are needed in which design, construction, operation, and end-of-life phases of a civil structure. It has to capture all data needs in each phase and cover services to process that data within integrated views and models in the digital twin.

4. Develop brown-field digital twin construction methods for existing civil structures: In the first step, such a method has to establish a digital representation of a civil structure without changing the physical object. It also requires updating existing models to fit planned ones.

5. Investigate model-driven approaches to react to changing software stacks and technologies: Model-driven development can help to reduce the problems, since the models usually abstract from technological details. Provided that the generators are maintained and updated appropriately, regeneration with an updated generator can automatically produce semantically identical software on a newer technology stack in the long run software systems for long-lasting civil structures.

We defined this initial research agenda to stimulate multidisciplinary research on digital twins of civil structures covering various models to face challenges related to natural disasters and critical infrastructures.

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