An IFC schema extension for BIM-based description of wastewater treatment plants

Heinrich Söbke¹, Patricia Peralta²*, Kay Smarsly² and Martin Armbruster³

¹Chair of Computing in Civil Engineering, Bauhaus University Weimar, Germany
²Institute of Digital and Autonomous Construction, Hamburg University of Technology, Germany
³hydrograv GmbH, Dresden, Germany

Abstract

Building information modeling (BIM) may advantageously be used to support life-cycle management of engineering structures. The Industry Foundation Classes (IFC) are a standardized BIM data format issued by the International Organization for Standardization to describe engineering structures, such as buildings, tunnels, and bridges. Although often employed for describing basic features of structures, the IFC standard is not capable of sufficiently describing the planning procedure of wastewater treatment plants, which is determined by functional aspects. This paper presents an IFC schema extension that supports BIM-based planning of wastewater treatment plants. A semantic model, serving as a formal basis for the IFC schema extension, is defined that contains the semantics describing the information used for planning of wastewater treatment plants. The IFC schema extension proposed in this study enables BIM-based description of wastewater treatment plants in compliance with the IFC standard, and it may serve as basis for wastewater treatment plant simulations.

Keywords: Building information modeling (BIM), Industry Foundation Classes (IFC), semantic modeling, metamodeling, wastewater treatment plants

*Corresponding author: patricia.peralta.abadia@uni-weimar.de
1 Introduction

Wastewater treatment plants are complex engineering structures that fulfill services vital to society. Uncertainties are present in planning wastewater treatment plants, which are typically designed for a service life of 30 years, due to the complexity of purification processes and the continuous urban growth (Manig et al., 2019). Various engineering disciplines are involved in the planning of a wastewater treatment plant (WWTP), such as fluid mechanics, structural design, and microbial engineering. Despite substantial advancements that have been made in digitalization, experts involved in planning procedures usually collaborate manually: Planners typically receive input information as hardcopies or in semantically unstructured file formats, such as PDF files (DWA, 2018). The input information is then transferred to different software tools used for planning. Finally, the planning results are made available, again, as hardcopies or in semantically unstructured file formats.

Traditional procedures render WWTP planning error-prone, time-consuming, and costly, the quality largely depending on the experience of the planners. The high efforts and costs required for planning also pose limitations to the number of design variants, for example regarding purification processes, tank configurations, and selecting technical equipment. To check each design variant during planning, wastewater treatment simulations are performed, where detecting and correcting errors in the input information consumes one third or more of the time spent for the simulations (Rieger et al., 2010). Faulty or erroneous simulations may lead to expensive design solutions or suboptimal performances. Hence, traditional planning procedures suffer from inefficient operation and poorly accessible data, information, and knowledge. Digitalizing planning procedures may thus improve the quality of wastewater treatment plants to be built, operated, and maintained, enhancing the economic and ecological performance of wastewater treatment plants in terms of energy efficiency and purification quality. Industry 4.0 has pushed for wider software support in planning and constructing wastewater treatment plants (DWA, 2018) that was previously overlooked as a significant factor to improve productivity in earlier studies (Mojahed & Aghazadeh, 2008). However, digitalization of planning and constructing wastewater treatment plants has not been fully implemented in practice.

For improving planning procedures, building information modeling (BIM) has been proven an effective tool in several engineering fields (Cheng & Chang, 2019). BIM provides a common data model for describing engineering structures accessible by all parties involved in planning (Theiler & Smarsly, 2018). Operating on a common data model facilitates the accessibility of information and the efficiency of planning (Smarsty & Tauscher, 2015). It is estimated that digitalizing planning procedures, as supported by BIM, will result in cost savings between 13% and 21% in the planning and construction
phase and between 10% and 17% in the operation phase (Gerbert et al., 2016). Benefits of implementing BIM in the construction of wastewater treatment plants have been reported by Bezant (2017). In addition to the economic advantages, considerable ecological gains, such as impacts on climate action and energy efficiency, are expected (EU BIM Taskgroup, 2017). A proof of concept of implementing BIM for decentralized wastewater treatment systems has been presented by Dariva & Araujo (2020), where BIM templates of seven wastewater treatment systems used in Brazil are developed in a proprietary BIM format, and their acceptance among the community has been evaluated. It has been revealed that, to widen the implementation of BIM for WWTP planning, a vendor-neutral description of wastewater treatment plants according to international technical standards is necessary.

The Industry Foundation Classes (IFC) currently represent the only standardized BIM data format, recognized by the International Organization for Standardization (ISO), the European Committee for Standardization (CEN), and the German Institute for Standardization (DIN). The IFC standard is maintained by the non-profit organization buildingSMART, and it is described by a general schema, the IFC schema (buildingSMART, 2018). The IFC schema is used as a formal basis for describing semantic information of buildings and infrastructure, including geometry and material. Extensions of the IFC schema have been proposed to support domain-specific information, such as IfcRoad and IfcBridge for describing infrastructure projects and IfcRail for describing rail tracks, which use the extension IfcAlignment as a foundation (buildingSMART, 2019a; Gao et al., 2016; Amann et al., 2015). Frameworks have been implemented in IFC environments linking sub-domain models that use generic constructs, as shown by Koch et al. (2017), for automating tunnel construction work. Furthermore, Industry 4.0-related structures, such as cognitive buildings, smart monitoring systems, and digital roads have also been described by extending the IFC schema (Ibanez et al., 2019; Theiler et al., 2018; Mirboland & Smarsly, 2019). Efforts have also been conducted to propose IFC-compliant descriptions of sewer systems. Bock & Michaelis (2019) have explored options of using IFC to support planning and operating sewer systems, while Hijazi et al. (2009) have proposed an approach to integrate IFC-based sewer network descriptions into geographical information systems. The combination of IFC-based sewer networks and sensor technologies to control sewer networks has been presented by Edmondson et al. (2018). However, describing wastewater treatment plants is not yet sufficiently supported by the IFC standard without employing generic constructs, such as proxy elements, user-defined property sets, and object type definitions. Generic constructs may lead to a loss of semantic information, due to ambiguity caused by the unavailability of predefined semantics in proxy elements and the lack of conventions in user-defined property sets and object type definitions (Theiler et al., 2018). Extending the IFC schema to describe planning of wastewater treatment plants may help overcome the inefficiencies of the current planning procedures described above and verify data completeness against a consensus among software tools and technical standards.
Each engineering discipline involved in WWTP planning maintains its own software tools, which import data from and export results back to certain platforms. Clearly, a standardized data exchange format improves interoperability between software tools available for each planning discipline. In this paper, the concept of an IFC-compliant description of wastewater treatment plants intended for planning is proposed as an IFC schema extension. Building on a preliminary study conducted by the authors (Söbke et al., 2018a), the IFC schema extension is developed based on a three-stage approach presented in the following sections. In Section 2, the first stage is shown, where a semantic model is developed that describes the information necessary for planning wastewater treatment plants. In the second stage, presented in Section 3, the semantic model is implemented into an IFC schema extension taking into account classes (i.e. IFC entities) and attribute lists (i.e. property sets) that exist in the current IFC schema “IFC 4 – Addendum 2”. The IFC schema extension is verified using test software of the official IFC certification program. In the third stage, an example is implemented using the IFC schema extension, as shown in Section 4. The example is used to validate the IFC schema extension proposed herein with respect to enabling BIM-based description of wastewater treatment plants. Finally, the paper concludes with a discussion of the results and a summary of this study.

2 A semantic model for wastewater treatment plants

In this section, the development of the semantic model to describe WWTP planning information is presented, detailing the process of planning a secondary clarifier as an illustrative example. The semantic model is developed in three steps by:

(i) Identifying typical information exchange requirements relevant to planning wastewater treatment plants,
(ii) Analyzing knowledge sources that specify the information to be included in the IFC schema extension, and
(iii) Creating the semantic model based on the information extracted from the knowledge sources.

It is worth mentioning that in this study, the information exchange requirements (step i) are identified in an iterative process by direct collaboration between two academic institutions and nine industrial partners. For identifying robust and accurate information exchange requirements, knowledge sources created by expert panels (e.g., technical standards) are selected for analysis, incorporating the consensus achieved in the knowledge sources into the information exchange requirements. For example, internationally recognized standards of the German Association for Water, Wastewater, and Waste (DWA) have iteratively been developed by experts in consensus-oriented approaches, available to the
entire community for review – using approaches similar to those applied for IFC standardization. The semantic model (step iii), comprising the information exchange requirements, is evaluated in the context of the working group of the DWA for establishing of BIM in water management (DWA, 2018) to achieve consensus among experts in water management.

When assembling the semantics from the information exchange requirements and the knowledge sources, it is important to be familiar with the operation of wastewater treatment plants. Therefore, before describing the development of the semantic model, the basic operation of wastewater treatment plants is explained, as illustrated in Figure 1 in terms of a flow chart. The flowchart represents the flow of the water to be purified through the components of wastewater treatment plants.

The flowchart shown in Figure 1, for illustration purposes, visualizes wastewater treatment plants using the “activated sludge” process. The wastewater flows into the preliminary treatment, in which coarse solids, such as toiletries and sand, are removed by racks and grit chambers. In the subsequent primary clarifier, further mechanical purification of the wastewater is performed by reducing the flow velocity. In the aeration tank, oxygen is provided by air supply enabling biological purification processes, such as bacterial degradation of nitrogenous and organic substances. In the secondary clarifier, the particulate matter (or “activated sludge”), consisting of the bacteria, incorporated degradation products, and inert particles, is separated from the purified water by gravity. The purified water leaves the WWTP and rejoins the receiving water body. While parts of the activated sludge are recirculated to the aeration tank (i.e. “return activated sludge”), the excess sludge (i.e. “waste activated sludge”) is thickened and disposed together with the sludge from the primary clarifier (Metcalf & Eddy Inc., 2014).

Figure 1: Flowchart of wastewater treatment plants.
During planning, the WWTP components are pre-designed and sized to satisfy technical capacity demands. Sizing guidelines exist for all WWTP components, with sizing of the aeration tanks and the secondary clarifiers being the most complex tasks (Leslie Grady et al., 2011). Biological processes taking place in the aeration tanks are influenced by environmental parameters, such as temperature. Besides, the efficiency of mechanical purification processes (sedimentation) taking place in the secondary clarifiers depends on the water circulation, which is in turn influenced, among other factors, by the inflow velocity and the tank geometry. In addition, the dimensions of the two tanks affect each other. Thus, the tanks are sized iteratively until the technical capacity demands are satisfied. Sizing secondary clarifiers, due to its complexity, serves as an illustrative example in the following subsections.

2.1 Information exchange requirements

Information exchange requirements illuminate the information that is used, generated, and exchanged in the different tasks of planning wastewater treatment plants. To analyze the information exchange requirements relevant to wastewater treatment plants, a process map is developed by the team of authors from academia and industry, as shown in Appendix A. The process steps correspond to the steps of conventional planning processes. The key particularity of WWTP planning is the large number of individuals and institutions involved in planning. As an example demonstrating the development of the IFC schema extension presented in this paper, the information exchange requirements for planning secondary clarifiers in the preliminary design phase are shown in Figure 2. The term “preliminary design” describes an early phase in the planning procedure defining types, numbers, and sizes of WWTP components to be used, and the term also denotes the result of the preliminary design phase. As shown in Figure 2, for planning secondary clarifiers, project managers communicate to planners WWTP design requirements, such as load specifications for technical capacity demands. Load specifications include measures of population equivalents (PE), measures of chemical oxygen demand (COD) load, or measures of phosphate load. The load specifications are used by planners to elaborate a preliminary design using sizing guidelines that are usually defined by technical standards. The sizing results include process loads, volumes, and surface areas, which are used to design the geometries and to model functional aspects of the WWTP components. Afterwards, the sizing results and preliminary design are communicated to the project managers for approval. Therefore, the information used, generated, and exchanged while planning secondary clarifiers is summarized as:

- Load specifications,
- Sizing results, and
- Preliminary design.
As a step towards standardization, the information exchange requirements allow the information to be interpreted without losing semantics. Compiling the information exchange requirements in a semantic model provides the basis for the IFC schema extension. In the following section, knowledge sources that include semantic information of wastewater treatment plants in the context of the information exchange requirements are identified and discussed.

<table>
<thead>
<tr>
<th></th>
<th>Preliminary design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project managers</strong></td>
<td></td>
</tr>
<tr>
<td>WWTP requirements</td>
<td>Project intent and constraint</td>
</tr>
<tr>
<td></td>
<td>Review approval</td>
</tr>
<tr>
<td><strong>Planning engineers</strong></td>
<td></td>
</tr>
<tr>
<td>Preliminary design</td>
<td>WWTP design</td>
</tr>
</tbody>
</table>

Figure 2: Exchange requirements relevant to planning secondary clarifiers (extract of the process map in Appendix A).

### 2.2 Knowledge sources

The information exchange requirements are stated in knowledge sources that are used for planning wastewater treatment plants. To identify the knowledge sources relevant to developing the semantic model, the following categories that provide information relevant to semantically describing wastewater treatment plants are defined:

- Standardized data formats,
- Software packages,
- Teaching material, and
- Technical standards.

In the field of technical water and wastewater infrastructure, a plenitude of standardized data formats exist (Ackermann & Bock, 2017), none of which capable of describing wastewater treatment plants as detailed as required for planning. The “design2treat” software package (GFSA, 2017), the “Aqua Designer” software package (BitControl GmbH., 2018), and the “Active Sludge Expert” software package (Fröse, 2017) are well-known for planning wastewater treatment plants. By analyzing the
software packages with respect to load specification and sizing results, information required for the semantic model is extracted. In addition, teaching material, as provided by Metcalf & Eddy Inc. (2014), Leslie Grady et al. (2011), and Water and Environment (2009), are knowledge sources providing insights into the preliminary design of wastewater treatment plants. Last, but not least, technical standards are highly recognized by planners as sizing guidelines. Since the DWA endeavors to strengthen their standards for applications outside Germany in moderate climatic zones covering a major part of the worldwide wastewater ( Wichern et al., 2019), this study is built on technical standards of DWA. The DWA A-131 standard describes sizing principles of wastewater treatment plants using activated sludge processes and the DWA A-198 standard describes standardized parameter sets for wastewater treatment plants (DWA, 2000, 2016; ATV-DVWK, 2003).

The information gathered from the knowledge sources are represented by parameters printed in italics and explained in the following paragraphs. The parameters are divided into four categories:

- Initial load specification parameters,
- Load specification parameters,
- Sizing result parameters, and
- Preliminary design parameters.

Initial load specifications define the required technical capacities of wastewater treatment plants, as shown in Table 1. Parameters, such as specific water consumption and infiltration water flow, are used to calculate the wastewater inflow to be treated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description [data type, unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>specificWaterConsumption</td>
<td>Water consumption per day and per inhabitant determines the amount of wastewater to be treated [real, L/PE/d].</td>
</tr>
<tr>
<td>infiltrationWaterFlow</td>
<td>Infiltration water flow describes the flow of infiltration water that reaches the wastewater treatment plant and must be treated as wastewater [real, L/s].</td>
</tr>
<tr>
<td>populationEquivalent</td>
<td>The population equivalent specifies a measure for the pollution load of the wastewater. The actual pollution load is determined using specific loads, as the pollution load depends on local characteristics [real, PE].</td>
</tr>
<tr>
<td>stormWaterCoefficient</td>
<td>The storm water coefficient denotes the share of rainwater in the wastewater [real].</td>
</tr>
</tbody>
</table>

Each structure in a WWTP has additional load specifications defined in the sizing guidelines that are used to model purification processes, as shown in Table 2. The load specifications describe specific loads in the wastewater (e.g. organic load, nitrogen load, and phosphate load) influencing the purification processes.
Table 2: Load specification parameters for secondary clarifiers according to the DWA A-131 standard.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description [data type, unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydraulicRetentionTime</td>
<td>Hydraulic retention time describes the time required for the wastewater passing through the primary clarifier [real, h].</td>
</tr>
<tr>
<td>specificXLoad</td>
<td>Specific solid (X) load defines the amount of filterable solids to be processed per day and per population equivalent [real, g/PE/d].</td>
</tr>
<tr>
<td>specificPLoad</td>
<td>Specific phosphate (P) load denotes the amount of phosphate to be processed per day and per population equivalent [real, g/PE/d].</td>
</tr>
<tr>
<td>specificNLoad</td>
<td>Specific nitrogen (N) load characterizes the amount of nitrogen to be processed per day and per population equivalent [real, g/PE/d].</td>
</tr>
<tr>
<td>specificCODLoad</td>
<td>Specific chemical oxygen demand (COD) load specifies the amount of oxidizable pollutants to be processed per day and per population equivalent [real, g/PE/d].</td>
</tr>
</tbody>
</table>

From applying the sizing guidelines, sizing results are obtained for each structure. Table 3 summarizes the sizing result parameters for secondary clarifiers according to the DWA A-131 standard. As part of sizing, the sizing result parameters are used to estimate the required volume, surface area, and retention time for each structure. According to the choice of the dimensions of the structure, the conformity with the minimal requirements is checked and the sizing result parameters are recalculated for the dimensions chosen for each structure.

Table 3: Sizing result parameters for the secondary clarifiers according to the DWA A-131 standard.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description [data type, unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickeningTime</td>
<td>Thickening time defines the time required for thickening the sludge until reaching the consistency required for further processing [real, h].</td>
</tr>
<tr>
<td>comparedSludgeVolume</td>
<td>Compared sludge volume is used for describing the settling characteristics and for controlling the purification process [real, L/m³].</td>
</tr>
<tr>
<td>totalSolidsReturnActivatedSludge</td>
<td>Total solids return of the activated sludge denotes the dry matter ratio of the return sludge [real, kg/m³].</td>
</tr>
<tr>
<td>totalSolidsInlet</td>
<td>Total solids of the inlet characterizes the dry matter ratio of the inlet [real, kg/m³].</td>
</tr>
<tr>
<td>totalSolidsBottomSludge</td>
<td>Total solids of the bottom sludge specifies the dry matter ratio of the bottom sludge [real, kg/m³].</td>
</tr>
<tr>
<td>returnSludgeFlow</td>
<td>Return sludge flow describes the flow of return sludge from the secondary clarifier back into the aeration tank [real, m³/h].</td>
</tr>
<tr>
<td>sludgeVolumeIndex</td>
<td>Sludge volume index is a measure for the settleability of the activated sludge in the secondary clarifier [real, mL/g].</td>
</tr>
<tr>
<td>sludgeVolumeSurfaceLoading</td>
<td>Sludge volume surface loading defines the loading flow of the tank and is the quotient of the inflow and the permissible surface loading [real, L/(m² h)].</td>
</tr>
<tr>
<td>surfaceFlowRate</td>
<td>Surface flow rate depends on the function of the tank and the passage time. It is the quotient of the tank inflow and the tank surface [real, m³/h].</td>
</tr>
</tbody>
</table>
In addition to the load specification parameters and the sizing result parameters, preliminary design parameters define the purification process and the geometry (i.e. profile) for each structure. Table 4 shows the preliminary design parameters relevant for secondary clarifiers. Parameters such as \textit{denitrification}, \textit{nitrification}, and \textit{perfusion type} are related to the purification process.

Table 4: Preliminary design parameters for secondary clarifiers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description [data type, unit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{denitrification}</td>
<td>Denitrification determines whether denitrification is carried out in the aeration tank influencing the sizing of the secondary clarifier [boolean].</td>
</tr>
<tr>
<td>\textit{denitrificationType}</td>
<td>Denitrification type describes the type of denitrification [enumeration: pre-anoxic, step-feed, simultaneous, alternating, intermittent, post].</td>
</tr>
<tr>
<td>\textit{nitrification}</td>
<td>Nitrification denotes whether nitrification is carried out in the upstream aeration tank influencing the sizing of the secondary clarifier [boolean].</td>
</tr>
<tr>
<td>\textit{perfusionType}</td>
<td>The perfusion type describes the type of flow of the sedimentation process, which must be aligned with the geometry of the secondary clarifier [enumeration: vertical, horizontal].</td>
</tr>
<tr>
<td>\textit{geometry}</td>
<td>The geometry characterizes the base plan of the tank [enumeration: round, rectangular].</td>
</tr>
<tr>
<td>\textit{numberOfTanks}</td>
<td>The number of tanks specifies the amount of tanks simultaneously purifying the wastewater [integer].</td>
</tr>
</tbody>
</table>

2.3 Semantic model

The information identified from the information exchange requirements and from the knowledge sources serves as the basis for the semantic model. The semantic model describes the information required for planning of wastewater treatment plants, including load specifications, sizing results and preliminary design parameters for WWTP components (Figure 1) as well as WWTP technical equipment. Figure 3 shows an extract of the semantic model in terms of a class diagram in the Unified Modeling Language, while the full model is provided in Appendix B. In this subsection, elements of the semantic model are printed in \textit{italics}.

Planning of wastewater treatment plants, as reflected in the semantic model by the class \textit{WastewaterTreatmentPlant}, requires initial load specification parameters (class \textit{LoadTuple}), WWTP structure (class \textit{Structure}), and technical equipment (class \textit{TechnicalEquipment}). The class \textit{Structure} is the superclass of all classes describing WWTP structural components, such as racks, trickling filters or tanks (e.g. \textit{SecondaryClarifier}). Since purification processes take place in the WWTP tanks, the tanks may also be referred to as “process spaces”. Process spaces, relevant to describing functional aspects of wastewater treatment plants, are hosting the biological, chemical, and physical processes. Functional aspects of a process space are modeled by the interface \textit{ProcessSpace}, which is implemented by the class \textit{Structure}. While the class \textit{LoadTuple} describes the initial load specification parameters, from which the quantity and quality of the wastewater is derived, the class \textit{ProcessSpaceLoad} describes the
load specification parameters for specific WWTP structures and for specific sizing guidelines. The sizing result parameters of a WWTP planning procedure are stored as subclasses of the class `ProcessSpaceResult` according to specific sizing guidelines and as attributes of the subclasses of the class `Structure` (e.g. subclass `SecondaryClarifier`). The class `ProcessSpaceResult` stores the sizing result parameters during sizing, from which the required dimensions of the WWTP structures are estimated. After the dimensions are chosen, the sizing result parameters are recalculated and stored in the corresponding subclass of the class `Structure`. Specifically, the subclass `ProcessSpaceLoadA131` of the class `ProcessSpaceLoad` contains the load specifications for a specific instance of secondary clarifiers subjected to sizing according to the DWA standard A131. Whereas multiple objects of the class `LoadTuple` assigned to an object of `WastewaterTreatmentPlant` class describe various load specifications required for sizing, e.g. loads influenced by weather conditions, the corresponding attributes of the `ProcessSpaceLoad` subclasses describe values actually applied for sizing WWPT structures. The preliminary design parameters that refer to purification processes are also described as attributes of the subclasses of the class `Structure`, while the preliminary design parameters that refer to the geometry are described with the class `TankGeometry`.

To illustrate the semantic model in more detail, Figure 4 shows the classes `ProcessSpaceLoadA131` and `SecondaryClarifier`. The class `ProcessSpaceLoadA131` contains load specification parameters describing the quantity and quality of the wastewater to be purified according to the DWA standard A131 as well as the initial load specification parameters (e.g. `populationEquivalent`, an attribute derived from the class `LoadTuple` employed for determining the quantity of wastewater to be purified). The attributes of the class `SecondaryClarifier` are divided into categories, which include:

- Sizing result parameters documenting the final results of planning procedures (e.g. `surfaceFlowRate`, a measure for describing the purification process), and
- Preliminary design parameters guiding the basic planning approach of wastewater treatment plants (e.g. `denitrification`, an attribute that describes the purification process).
In addition to assigning attributes directly to a class that describes a certain WWTP component (Figure 1), specific classes are provided for clustering attributes. For example, the class *TankGeometry* describes the shape of a tank, a preliminary design parameter, together with the dimensions of the tank (Figure 4). Since dimensions depend on the tank shape, the class *TankGeometry* is defined as a superclass, whose attributes are inherited by subclasses that specify the tank shape, i.e. *RoundTankGeometry* or *RectangularTankGeometry* (Figure 3). In the following section, the semantic model presented is mapped into an IFC schema extension.
3 IFC schema extension

This section describes the mapping of the semantic model onto the IFC schema, which covers (i) alignment of the semantic model with the current IFC schema, (ii) implementation of the IFC schema extension, and (iii) verification of the IFC schema extension. For the sake of clarity, the description of information required for planning a secondary clarifier using the IFC schema is outlined in detail. In the following subsections, elements of the current IFC schema, the IFC schema extension, and the semantic model are printed in italics.

3.1 Alignment of the semantic model with the current IFC schema

As a preliminary step towards developing the IFC schema extension, the alignment aims at reusing schema elements, such as IFC entities and property sets, as well as core concepts of the current IFC schema, IFC4 ADD2. The alignment reduces the efforts required to develop new IFC entities and
property sets. In addition, the IFC schema extension development is carried out in accordance with well-known core concepts allowing users to become easily familiar with the IFC schema extension. The following concepts are used to align the semantic model with the current IFC schema:

(i) **Identification of reusable IFC entities of the current IFC schema**: The classes of the semantic model are compared with the existing IFC entities. An example is the IFC entity *IfcSensor* of the current IFC schema to describe the class *MeasuringInstrument* of the semantic model.

(ii) **Identification of reusable property sets**: Similar to IFC entities, property sets of the current IFC schema are reused to map attributes of the semantic model.

(iii) **Application of IFC core concepts**: The IFC schema is developed according to so-called IFC core concepts, such as *port nesting* and *object typing*. Port nesting supports connecting devices with each other via cables or pipes. For wastewater treatment plants, port nesting advantageously describes the connection of WWTP tanks along the flowchart. Object typing refers to using a pair of IFC entities for a class: The first IFC entity describes the concrete instance (object occurrence entity) and the second IFC entity holds information identical for all specific instances (object type entity). An example of object typing is the pair of IFC entities *IfcPump* and *IfcPumpType*: The serial number of a pump is described by the attribute *IfcIdentifier* of the entity *IfcPump*. Besides, the building type of the pump is described by the *ElementType* attribute of the *IfcPumpType* entity inherited from the *IfcElementType* entity. Each instance of an object occurrence entity of the type *IfcPump* is assigned an instance of the object type entity of the type *IfcPumpType*.

(iv) **Application of IFC design patterns**: Some design concepts are not supported by the current IFC schema, but IFC core concepts may be used as templates for developing certain aspects of the IFC schema extension. For example, the class *ProcessSpaceLoadModel* of the semantic model may be described through a design pattern analogous to the IFC entity *IfcStructuralAnalysisModel*, which assembles the information required to represent a structural analysis model.

(v) **Repurposing of existing IFC entities**: Existing IFC entities are used for purposes not immediately apparent from the original design goal of the entities. The entity *IfcSpace*, which defines an actual or a theoretical bounded volume, may be regarded as an option for mapping process spaces onto the IFC schema. For other IFC entities, the benefit is as well obvious, for example *IfcObjectAssembly* is used when groups of objects are to be generated.

In addition to the concepts mentioned above, standard rules are considered when aligning the semantic model with the current IFC schema. A standard rule includes the integration of units assigned to new properties, which are added to the IFC schema extension and are not present in the current IFC
schema. For example, the value of the property `specificCODLoad`, a parameter describing the COD load, corresponds to the unit “gram per population equivalent per day” (g/PE/d).

As a result of the alignment, the need for additional entities and property sets to satisfy the information exchange requirements is identified. Considering the distinct functional aspects and the geometry complicity of WWTP structures and specialized technical equipment, new entities are preferred (i) to avoid issues regarding inheritance and (ii) to ensure user-friendliness. For example, specific entities are needed to represent load specifications and sizing results in process spaces, reflected in the semantic model through the classes `ProcessSpaceLoad` and `ProcessSpaceResults`, as well as structures and equipment specific to wastewater treatment plants, such as secondary clarifiers (class `SecondaryClarifier`). The IFC schema has four layers, the `core layer` contains the kernel, the `resource layer` offers basic data structures for the IFC schema, the `interoperability layer` includes IFC entities that are used across several disciplines, and the `domain layer` provides discipline-specific IFC entities. Representing an elementary design decision, the choice of the IFC schema layer plays an important role for interpreting the new IFC entities. For example, a new IFC entity to describe the subclass `SecondaryClarifier` of the semantic model is integrated into the `interoperability layer`, whereas specific technical equipment required for wastewater treatment plants is integrated into the `domain layer`.

### 3.2 Implementing the IFC schema extension

Mapping the semantic model onto the IFC schema, the IFC schema extension proposed in this study is described in a schema file using the data modeling language EXPRESS. New entities are added to describe process spaces (`IfcProcessSpace`), process space load models (`IfcProcessSpaceLoadModel`), and wastewater treatment plant specific structures, including tanks (`IfcWwtpTank`), geometries (`IfcTankGeometry`), and specialized technical equipment (`IfcWwtpTechnicalEquipment`). An overview of the existing IFC entities that are reused or repurposed and the new entities is presented in the Appendix C.

The current IFC schema file (IFC 4 ADD 2) is extended using the buildingSMART software package `ifcDoc` (buildingSMART, 2019b), where the current IFC schema and the proposed IFC schema extension are consolidated in a single schema file. The software package `ifcDoc` offers a graphical user interface that supports modifying schema files, and a further function is the graphical representation of the schemas using graphical notations, such as EXPRESS-G. In Figure 5, an extract of the IFC schema extension is presented in EXPRESS-G notation, where the existing IFC entities are highlighted in dark gray.
Wastewater treatment plants are represented by the central entity IfcWWTP, which is associated to the WWTP structures (IfcWWTPStructure). The IFC entity IfcBuilding is repurposed to accommodate all standard information of the WWTP structure. The entity IfcWWTPStructure has an association to technical equipment (IfcTechnicalEquipment), flow elements (IfcDistributionFlowElement), and measuring instruments (IfcDistributionControlElement). The IFC entity IfcDistributionFlowElement is reused to define elements that distribute the wastewater through the WWTP tanks, such as pipe segments (IfcPipeSegment), pipe fittings (IfcPipeFitting) and pumps (IfcPump). Likewise, the IFC entity IfcDistributionControlElement is reused to describe measuring instruments such as IfcSensor and IfcFlowInstrument.

Figure 5: Extract of the IFC schema extension in EXPRESS-G notation, where the existing IFC entities are highlighted in dark gray.

The entity IfcWWTPStructure is the super entity for IfcWWTPTank, which represents WWTP tanks. Analogous to IfcWWTPStructure, the tank specific standard information is represented by an association to the entity IfcTank. The entity IfcWWTPTank has an association to standard tank geometries.
IfcTankGeometry) and to process spaces (IfcProcessSpace). The entity IfcProcessSpace repurposes the IFC entity IfcSpace to store the space standard information and describes the processes occurring in the WWTP tanks and the sizing of the WWTP tanks. Furthermore, IfcProcessSpace has an association to the entity IfcProcessSpaceLoadModel, which allows the description of the sizing of the WWTP tanks. The complete IFC schema extension is attached as a digital resource to this paper. In the following paragraphs, details on implementing the IFC schema extension are provided, using a secondary clarifier as an example.

As an example showcasing the implementation of the IFC schema extension, Figure 6 and Figure 7 show the entities IfcProcessSpaceLoadA131 and IfcSecondaryClarifier in EXPRESS-G notation. The entities are shown on the left, while the attributes and the respective data types are visualized on the right. Figure 7 depicts the entity IfcSecondaryClarifier and the associated entity IfcProcessSpaceResultsA131 describing the sizing results according to the DWA standard A131, which are estimated from the load specifications described in the entity IfcProcessSpaceLoadA131 (Figure 6). Figure 7 also includes measures being part of the IFC schema extension, such as the type entity IfcComparedSludgeVolumeMeasure for the attribute ComparedSludgeVolume, which describes the settling characteristics of the sludge for controlling the purification process.

Listing 1 shows a section of the IFC schema extension that corresponds to Figure 7. In Listing 1, the entity IfcSecondaryClarifier is a subtype of the entity IfcWWTPTank, defined in the IFC schema.
extension. Furthermore, measures defining types and units of attributes and properties are introduced, which do not exist in the current IFC schema. For example, for the attribute SludgeVolumeIndex, the type entity IfcSludgeVolumeIndexMeasure is defined using the unit mL/g. In addition, the type entity IfcComparedSludgeVolumeMeasure (unit: L/m^3) is required for the attribute ComparedSludgeVolume, where its value is determined by multiplying the total solids and the sludge volume index. In the following subsection, the compliance of IFC files with the IFC schema extension is verified.

Figure 7: EXPRESS-G notation of the IfcSecondaryClarifier entity.
ENTITY IfcSecondaryClarifier
  SUBTYPE OF (IfcWwtpTank);
  DimensionedBy : SET [0:?] OF IfcProcessSpaceResultA131;
END_ENTITY;

ENTITY IfcProcessSpaceResultA131
  SUBTYPE OF (IfcProcessSpaceResult);
  Denitrification : IfcBoolean;
  DenitrificationType : IfcDenitrificationTypeEnum;
  Nitrification : IfcBoolean;
  PerfusionType : IfcPerfusionTypeEnum;
  ThickeningTime : IfcTimeMeasure;
  ComparedSludgeVolume : IfcComparedSludgeVolumeMeasure;
  TotalSolidsReturnActivatedSludge : IfcMassDensityMeasure;
  TotalSolidsInlet : IfcMassDensityMeasure;
  TotalSolidsBottomSludge : IfcMassDensityMeasure;
  ReturnSludgeFlow : IfcVolumetricFlowRateMeasure;
  SludgeVolumeIndex : IfcSludgeVolumeIndexMeasure;
  SludgeVolumeSurfaceLoading : IfcLinearVelocityMeasure;
  SurfaceFlowRate : IfcLinearVelocityMeasure;
INVERSE
  DimensionedFor : IfcSecondaryClarifier FOR DimensionedBy;
END_ENTITY;

TYPE IfcDenitrificationTypeEnum = ENUMERATION OF
  (PREANOXIC, STEPFEED, SIMULTANEOUS, ALTERNATING, INTERMITTENT, POST);
END_TYPE;

TYPE IfcPerfusionTypeEnum = ENUMERATION OF
  (VERTICAL, HORIZONTAL);
END_TYPE;

TYPE IfcComparedSludgeVolumeMeasure = REAL;
END_TYPE;

TYPE IfcSludgeVolumeSurfaceLoadingMeasure = REAL;
END_TYPE;

TYPE IfcDerivedMeasureValue = SELECT
  (IfcAbsorbedDoseMeasure
   ...
   ,IfcComparedSludgeVolumeMeasure
   ,IfcSludgeVolumeSurfaceLoadingMeasure
   ,IfcWarpingMomentMeasure);
END_TYPE;

Listing 1: Extract of the IFC schema extension (EXPRESS format), defining the IfcSecondaryClarifier
and IfcProcessSpaceResultA131 entities and the respective attributes.

3.3 Verification of the IFC schema extension

The verification procedure conducted in this study determines whether the contents of the IFC schema
extension proposed in the previous subsection and the corresponding IFC files are structured according
to the IFC standard. In this study, the IFC files, materializing the IFC schema extension to support
WWTP planning, are created using a Java-based software application that is integrated with an IFC Java
framework for accessing and visualizing IFC files (Apstex GbR, 2019). The software application
incorporates the IFC schema file, which consolidates the current IFC schema and the IFC schema
extension presented in the previous subsection, in EXPRESS format. With the IFC Java framework,
Java classes are generated from the IFC schema file using a compiler-compiler approach. The Java classes are used by the Java-based software application for creating IFC files describing the information used for planning wastewater treatment plants. Then, the IFC files are verified with respect to compliance with the IFC schema extension.

The syntactic correctness of the IFC files generated is checked by the software application known as “b-Cert” (Iabi e.V., 2019), which is the basis of the official buildingSMART certification platform to check IFC files compliance with the IFC standard. As a result of the verification process, it is shown that IFC files compatible with the IFC standard are generated with the software application. In the following section, the IFC schema extension is validated through an example WWTP.

4 Validation of the IFC schema extension for an IFC-compliant description of wastewater treatment plants

Following the verification of the IFC schema extension, the validation of the IFC schema extension checks whether the IFC schema extension can be used for an IFC-compliant description of wastewater treatment plants. Precisely, it is checked whether describing all information necessary for planning a WWTP is possible using an IFC file incorporating the IFC schema extension. Hence, while the verification is conducted automatically, analyzing the syntactic conformance of the IFC files and the rules defined within the IFC schema, the validation examines the semantic conformance of the IFC files by matching the information exchanged with the previously defined information exchange requirements. The validation is done in two steps, (i) checking visualization and readability and (ii) checking content. Prior to the two-step validation procedure, an IFC model of the preliminary design of an example WWTP composed of a rack chamber and a grid chamber, two primary clarifiers, two aeration tanks, two secondary clarifiers, and an outlet is developed using the Java-based software application described in Section 3.3 and the corresponding IFC file is generated (Figure 8). With the Java-based software application, instances of the Java classes corresponding to WWTP components (e.g., IfcRack, IfcPrimaryClarifier, IfcAerationTank, IfcSecondaryClarifier, and IfcOutletStructure), including process spaces, geometry and relationships, are generated. In accordance with the IFC standard, object typing concepts are used to describe the instances of the WWTP tanks in the IFC model, while the port nesting concept is used to describe the pipes connecting the tanks. The IFC file incorporates the new entities defined in the IFC schema extension, such as IfcProcessSpace and IfcWwtpTank. For illustration purposes, the description of one of the secondary clarifiers is discussed in detail in the remainder of the section.

To check the visualization and readability, the IFC file is tested to confirm that the information of the secondary clarifier can be read and visualized in the viewer environment of the Java-based software
application. As shown in Figure 8, the WWTP structures and process spaces are visualized and the attributes are readable by the Java-based software application. The tank geometry is selected within the sizing procedure by the planner from a set of standard tank geometries. The parameters describing the geometry are contained in the entity *IfcTankGeometry* with subentities specific to each standard tank geometry, such as the subentity *IfcRoundTankGeometryFunnel*.

![Figure 8: Visualization of an IFC model describing a wastewater treatment plant.](image)

To check the content, the load specification required for sizing and the sizing results are revised with the information contained in the IFC files. The load specifications required for sizing a secondary clarifier consist of parameters described in the IFC file as attributes of the entity *IfcProcessSpaceLoadA131* (Listing 2). It should be noted that the parameters already consider the population equivalents where necessary. The sizing results determine the dimensions of the tank geometry and functional aspects of the tank, such as purification processes. The results are embedded in the IFC file as attributes of the entity *IfcProcessSpaceLoadA131*, as shown in Listing 3, and as elements of property sets. The validation has proven that the proposed IFC schema extension accommodates all information required for planning secondary clarifiers.
5 Discussion

In this study, an IFC schema extension has been presented to support planning of wastewater treatment plants. Planning of secondary clarifiers has been used as an implementation example to validate the IFC schema extension. As a result of the validation, it has been proven that all information required for describing the planning of secondary clarifiers can be stored and exchanged using the IFC schema extension. Extracts of the IFC schema extension describing wastewater treatment plants have been presented at various conferences related to BIM and urban water management (e.g., Smarsly & Söbke, 2019; Söbke et al., 2018a; Söbke et al, 2018b) fostering a further discourse within the water management community to incorporate feedback into the IFC schema extension.

Although the IFC schema extension has not yet attained IFC standard status, it will promote the seamless use of BIM for planning wastewater treatment plants, i.e. further considerations may be taken
into account for a subsequent standardization process of the IFC schema extension. It must be emphasized that the IFC schema extension has been defined according to German standards. Studies have shown that differences between German and further national or international standards applied in moderate climate zones are marginal (Biccari & Heigener, 2018). Therefore, it is expected that the IFC schema extension proposed here can easily be internationally adapted to qualify as a candidate for an official IFC schema. In addition, adjustments are easily possible if new technical standards are to be described by the IFC schema extension. For example, for wastewater treatment plants, a fourth treatment stage, such as removal of micro-pollutants (after rake treatment, preliminary treatment, and biological treatment), is under discussion in the community. Furthermore, extending the IFC schema to include information exchange requirements of further purifying processes is a straightforward task. Likewise, predefined IFC-based WWTP component descriptions for prefabricated structures and specialized technical equipment may be added into the IFC-based description of the WWTP.

It can be expected that a standardization process transforming the IFC schema extension into an official IFC schema release will take several years. The study presented in this paper may form part of the documentation for the IFC schema extension, which is being formalized in information delivery manuals. In the meantime, generic IFC mechanisms, such as proxy elements, user-defined property sets, and object type definitions, may be used to exchange the information included in the IFC schema extension. The generic IFC mechanism approach may be applied to facilitate using software without access to the IFC schema extension, such as IFC viewers. For exchanging the corresponding IFC models, however, both sender and receiver of the IFC files must have reached an agreement in advance on how to exchange the information to avoid losing semantics.

6 Summary and conclusions

The Industry Foundation Classes (IFC) in its current version cannot be used for planning of wastewater treatment plants without employing generic constructs. In this study, an IFC schema extension for describing the planning of wastewater treatment plants has been proposed, building upon a semantic model. Knowledge sources, such as German standards and planning software packages, have been identified, categorized, and analyzed as a basis of the semantic model. The semantic model has been mapped onto the IFC schema and verified employing the test software used by the official IFC certification program. The IFC schema extension has been validated through planning of a secondary clarifier. In summary, the proposed IFC schema extension enables IFC-based descriptions of wastewater treatment plants and supports collaborative planning and interoperability with regard to functional aspects. Information on load specifications, sizing results, and design parameters applied in planning procedures may be documented on an IFC-compliant basis. As a result, planning procedures of
wastewater treatment plants may formally be verified and decision-making procedures are more comprehensive, more consistent, more transparent, and efficient as compared to traditional planning procedures. Finally, the IFC schema extension proposed in this study may serve as a point of departure towards an IFC standardization process for wastewater treatment plants, enabling IFC-based wastewater treatment plant simulations.

**Acknowledgments**

The authors gratefully acknowledge the financial support provided by the German Federal Ministry of Education and Research (BMBF) through grant FKZ 01IS17007C provided for the “ILMA” project (“Integral life-cycle management for wastewater treatment”) and the German Research Foundation (DFG) through grant SM 281/7-1. Further, the authors would like to thank Michael Theiler and Dr. Eike Tauscher from Apstex GbR for their valuable support in verifying and validating the IFC files. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of institutions mentioned above.

**References**


