BIM-based sizing of reactors in processing facilities

Heinrich Söbke*, Patricia Peralta Abadia, Dominik Heigener, and Kay Smarsly
Bauhaus University Weimar, Germany
heinrich.soebke@uni-weimar.de

Abstract. Processing facilities, such as wastewater treatment plants or biogas plants, are complex engineering structures that convert input streams to output streams using physical, biological, or chemical processes. When planning, constructing, and operating processing facilities, a large number of experts are involved, typically collaborating by exchanging unstructured files or even physical hardcopies, rendering planning, constructing, and operating of processing facilities costly and error prone. A promising approach towards improving processing facilities planning, while reducing cost and errors, is based on building information modeling (BIM). Using standardized data exchange formats, such as the Industry Foundation Classes (IFC), BIM supports digital planning of buildings. However, the IFC are currently incapable of describing information required for planning processing facilities, particularly information required for sizing of reactors, which is a crucial task in planning processing facilities. Advancing BIM-based planning of processing facilities, an IFC schema extension to support sizing of reactors is proposed in this paper. With the IFC schema extension, a semantic basis is provided to enable BIM-based sizing of reactors, as exemplarily illustrated by means of biogas plants.

1. Introduction
Processing facilities are complex structures that convert input streams to output streams using physical, biological, or chemical processes. Processing facilities are part of technical infrastructure, such as wastewater treatment plants, incineration plants, waterworks, or biogas plants. By transforming natural resources or waste into usable or disposable materials, processing facilities fulfill vital services to society.

The core of each processing facility is a reactor that hosts the conversion processes. Sizing of reactors is a task required for planning processing facilities, which aims to determine appropriate sizes and output streams of processing facilities. Sizing of reactors, due to the complexity of the processes involved, requires close collaboration of experts (“planners”) of fluid mechanics, environmental engineering, structural engineering, chemical engineering, and microbial engineering. Despite the advancements in digitalization recently made in the context of Industry 4.0, as discussed in Tay et al. (2018), planners of processing facilities still collaborate on a manual basis, using spreadsheets or hardcopies. The common procedure followed to plan processing facilities is characterized by information breaks caused by manual information exchange that is time-consuming and error-prone. In addition, not all types of processing facilities follow dedicated standards and guidelines that clearly define the planning procedures to be followed, i.e. the information requirements may vary even within a single discipline, depending on the experience of the planners. Thus, improved planning is required to minimize time and errors through enhanced information storage and exchange relevant to sizing of reactors to advance planning, construction, and operation of processing facilities.

Building information modeling (BIM) supports digital planning, construction, and operation of buildings. Sizing of reactors in processing facilities may be advanced by BIM-based information storage and exchange, in that various planning options may be documented, stored, and optimized, facilitating the collaboration between planners. The Industry Foundation Classes (IFC) are a standardized open BIM data exchange format (buildingSMART, 2018). The IFC, continuously being extended to broaden the scope of application, have originally been
designed to exchange building information, primarily geometry and material information (Laakso & Kiviniemi, 2012). Recently, the IFC have been used to describe processing facilities, such as wastewater treatment plants (Söbke, et al., 2018) or related infrastructure, such as sewer systems (Bock & Michaelis, 2019). However, sizing of reactors in processing facilities based on the IFC has received limited attention.

This study aims to develop an IFC schema extension to support sizing of reactors in processing facilities. Although the concept proposed herein, thus the IFC schema extension, is generic and extensible towards several reactor types, this study, for the sake of clarity, will exemplarily focus on reactors (more precisely, anaerobic digestion reactors) in biogas plants. In the reminder of the paper, the methodology and the semantics of the IFC schema extension are presented, followed by the implementation and validation of the IFC schema extension and concluding summary.

2. Semantics of the IFC schema extension for sizing reactors

In a previous study conducted by Söbke et al. (2018), a framework for an IFC schema extension for BIM-based description of wastewater treatment plants has been proposed, hereinafter termed “WWTP IFC extension”. Building upon the previous work, the WWTP IFC extension is used as a basis for describing information relevant to sizing reactors in processing facilities. As an example, the information needed for sizing an anaerobic digestion reactor (ADR) in a biogas plant is semantically described, showing that the approach presented herein qualifies as a basis to formalize sizing of reactors. In this section, a general approach for sizing of reactors is derived from the WWTP IFC extension, followed by a concise description of anaerobic digestion reactors. Then, the semantic model for conceptually describing anaerobic digestion reactors is presented and converted into the IFC schema extension for sizing reactors.

2.1 Sizing reactors in processing facilities

The WWTP IFC extension of the previous study is centered on an entity submodel, proposed to describe wastewater treatment plants based on a semantic model. The sizing of reactors in wastewater treatment plants is determined by the given loads (planning specifications), design decisions, and calculations defined by standards, such as the German DWA standard A 131 (DWA, 2000), or computational fluid dynamic (CFD) models. For example, the DWA standard A 131 describes different load cases with different wastewater volumes that define the technical capacity of the reactors, such as dry weather inflow, maximum inflow, or lowest temperature inflow. Each load case is used as input for the calculations, giving sizing results as output. Hence, sizing of reactors may be formalized as a semantic model representing a further abstraction comprised by loads and corresponding sizing results, analogous to a structural analysis model.

Figure 1 shows the semantic model, describing all information needed for sizing reactors in a processing facility, where the classes highlighted in grey are specific for one of the reactors in a wastewater treatment plant. As shown in Figure 1, the ProcessSpace interface corresponds to a reactor (i.e., a tank), and the entity ProcessSpaceLoadModel is intended to describe the loads and sizing results of a reactor. Using the ProcessSpace interface, one or more instances of the ProcessSpaceLoadModel may be assigned to a tank. The ProcessSpaceLoadModel contains aggregations to the ProcessSpaceLoadGroup and to the ProcessSpaceResultGroup. In the ProcessSpaceResultGroup, sizing results are stored, according to the loads described by the ProcessSpaceLoadGroup. A ProcessSpaceLoadGroup has an aggregation to one or more ProcessSpaceLoads, which are necessary for sizing in compliance with load cases defined in a
distinct standard. In the semantic model, each load case is represented by a ProcessSpaceLoad, and the sizing results are stored in a ProcessSpaceResult. All load cases are combined using a ProcessSpaceLoadGroup/ProcessSpaceResultGroup pair, entailing the final design specification of a specific reactor.

![Semantic Model Diagram](image.png)

Figure 1: Extract of the semantic model for sizing reactors in a processing facility.

Each reactor in a processing facility has specific input parameters (loads) and output parameters (sizing results) that may vary according to the different standards. Subclasses of ProcessSpaceLoad and ProcessSpaceResult may be defined to describe each standard. For example, in Figure 1, subclasses of ProcessSpaceLoad and of ProcessSpaceResult are defined to describe sizing according to CFD models and to the DWA standard A131.

### 2.2 Anaerobic digestion reactors for biogas plants

To describe the semantics of the IFC schema extension for sizing of reactors, an anaerobic digestion reactor for biogas plants, the illustrative example in this study, is formalized. The prevalence of biogas plants in Germany has considerably increased in the course of the so-called “Energy Revolution” (Renn and Marshall, 2016). With ongoing spreading of biogas...
plants, the demand for digitally supported planning (and, therefore sizing) is expected to further increase.

Anaerobic digestion is a sequence of microbiological processes that decompose biodegradable material (“biomass”) by microorganisms under absence of oxygen. Anaerobic digestion is applied in waste management as a waste treatment method or for supplying regenerative energies. Anaerobic digestion has two main products, (i) biogas, consisting of methane and carbon dioxide, and (ii) digestate, a reduced-volume bacterial biomass. Biogas is an energy source that may be harnessed as regenerative energy via cogeneration of heat and electricity, while digestate may be used as fertilizer. The type of reactor hosting anaerobic digestion processes depends on the waste to be treated and on the final use to be given to the waste. A more detailed description of anaerobic digestion and types of reactors can be found in Mata-Alvarez (2003).

2.3 A semantic model for sizing anaerobic digestion reactors

The semantic model developed to support sizing of anaerobic digestion reactors, as mentioned earlier, is based on the semantic model derived from the WWTP IFC extension of the previous study conducted by the authors, as shown in Figure 1. To extend the semantic model towards anaerobic digestion reactors, in essence, specific subclasses of ProcessSpaceLoad for the input streams and specific subclasses of ProcessSpaceResult for the output streams are defined. To semantically describe further details relevant to sizing of anaerobic digestion reactors, sources that provide detailed knowledge are identified, analyzed, and formalized, complemented by expert interviews. Serving as knowledge sources, a plenitude of standards, guidelines, and research projects exist, such as simulation models of anaerobic digestion processes (Batstone et al., 2002). In addition, the Association of German Engineers (VDI, 2006) characterizes substrates and the influence on biogas formation, which is also outlined by Weinrich et al. (2018). Furthermore, sizing concepts have been proposed by Garcia-Heras (2003) and Paterson et al. (2015), concluding that the current planning practice of anaerobic digestion reactors is strongly influenced by tacit knowledge gained by long-term experience. Similarly, standards of the German Association for Water, Wastewater and Waste (DWA) are implicitly related to anaerobic digestion reactors, although not explicitly addressing the reactor sizing. For example, the DWA-M 380 guideline describes co-fermentation of various substrates (DWA, 2009), the DWA-M 363 guideline describes origin, treatment, and utilization of biogas (DWA, 2010), and the M-372 standard (ATV-DVWK, 2003) describes sizing of anaerobic digestion reactors as a sub-aspect of the standard.

To create the semantic model, the sizing parameters determined from the above knowledge sources are defined and, in a subsequent step, formalized in the semantic model. Taking into account different anaerobic digestion reactor types, the sizing parameters are divided into three categories,

i. configuration parameters (representing the characteristics and operation of reactors),
ii. input parameters (representing input streams), and
iii. output parameters (representing output streams).

Table 1 shows the configuration parameters that define the characteristics and operation of anaerobic digestion reactors, such as type of anaerobic digestion and operating temperature.
Table 1: Sizing anaerobic digestion reactors: Configuration parameters.

<table>
<thead>
<tr>
<th>Configuration parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>methodOfDigestion</td>
<td>Enumeration describing the method applied for anaerobic digestion (enumeration values: wet, dry). In wet reactors, the substrate is liquid, and it is stirred or pumped, while in dry reactors the substrate is stacked.</td>
</tr>
<tr>
<td>modeOfOperation</td>
<td>Enumeration describing the method of operation (enumeration values: continuous, discontinuous). In continuous mode, the substrate is continuously fed into the reactor, with concurrent removal of processed substrate. In discontinuous mode (or batch mode), the reactor is filled to capacity and emptied once the process is complete.</td>
</tr>
<tr>
<td>typeOfReactor</td>
<td>Enumeration describing the reactor type (enumeration values: suspended, fixed film). In suspended reactors, the processes are executed in liquid, whereas in fixed film reactors, the anaerobic digestion processes take place on the surface of solids.</td>
</tr>
<tr>
<td>processTemperature</td>
<td>Temperature of the substrate being digested (double value, representing °C). Depending on the temperature, the process type is determined, either mesophilic (30 °C – 37 °C) or thermophilic (60 °C – 70 °C).</td>
</tr>
</tbody>
</table>

The input parameters, primarily required to characterize the substrate for calculating the expected gas yield, are shown in Table 2. In general, organic dry matter (OTS) is the most common parameter, while carbohydrates, lipids, and proteins allow a more accurate calculation of the biogas yield.

Table 2: Sizing anaerobic digestion reactors: Input parameters.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Description (data type, unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>substrateInputstream</td>
<td>Daily volume flow of the substrate (double, m³/d).</td>
</tr>
<tr>
<td>oTS</td>
<td>Substrate parameter organic dry matter (OTS) (double, kg/m³).</td>
</tr>
<tr>
<td>carbohydrates</td>
<td>Substrate parameter carbohydrates (double, kg/m³).</td>
</tr>
<tr>
<td>lipids</td>
<td>Substrate parameter lipids (double, kg/m³).</td>
</tr>
<tr>
<td>proteins</td>
<td>Substrate parameter protein (double, kg/m³).</td>
</tr>
<tr>
<td>tC</td>
<td>Substrate parameter total organic carbon (TC) (double, kg/m³).</td>
</tr>
<tr>
<td>dOC</td>
<td>Substrate parameter dissolved organic carbon (DOC) (double, kg/m³).</td>
</tr>
<tr>
<td>cCOD</td>
<td>Substrate parameter chemical oxygen demand (COD) (double, kg/m³).</td>
</tr>
<tr>
<td>meanResidenceTime</td>
<td>Parameter of operation, residence time of the substrate in the reactor (double, days). For wet reactors, the mean residence time is the hydraulic retention time.</td>
</tr>
<tr>
<td>loadingRatePerUnitVolume</td>
<td>Ratio of the daily load to the fermenter volume (double, kg/m³·d).</td>
</tr>
</tbody>
</table>

Table 3 describes the output parameters. Among the most relevant parameters with respect to the output stream is the effective reactor volume. The other parameters are related to the digestate and biogas production. The efficiency of a reactor is described by the digester gas efficiency, as a key performance indicator to evaluate the planning quality.
Table 3: Sizing anaerobic digestion reactors: Output parameters.

<table>
<thead>
<tr>
<th>Output parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>effectiveReactorVolume</td>
<td>Reactor volume required to process the input stream (double, m³).</td>
</tr>
<tr>
<td>digestateOutputstream</td>
<td>Daily volume flow of the digestate (double, m³/d).</td>
</tr>
<tr>
<td>digesterGasFlowRate</td>
<td>Daily volume flow of gas (double, m³/d).</td>
</tr>
<tr>
<td>methane</td>
<td>Gas parameter methane (double, m³/m³).</td>
</tr>
<tr>
<td>oTS</td>
<td>Digestate parameter organic dry matter (OTS) (double, kg/m³).</td>
</tr>
<tr>
<td>digesterGasEfficiency</td>
<td>Gas per OTS dry mass (double, m³/kg).</td>
</tr>
</tbody>
</table>

Figure 2 shows the main classes of the semantic model for sizing anaerobic digestion reactors, developed based on analyzing the knowledge sources and, specifically, the parameters relevant to sizing anaerobic digestion reactors. The classes ProcessSpaceLoad and ProcessSpaceResult are known from the semantic model of the WWTP IFC extension. Extending these classes, the subclasses ProcessSpaceLoadADR and ProcessSpaceResultADR include the attributes required for sizing anaerobic digestion reactors.

![Figure 2: Main classes of the semantic model for sizing anaerobic digestion reactors.](image)

3. Implementation of the IFC schema extension for sizing reactors

In this section, the proposed semantic model is implemented into the IFC schema extension for sizing reactors. The IFC schema extension proposed in this study is compliant to IFC version “IFC 4 – Addendum 2”, or “IFC4” for short (buildingSMART, 2017). Figure 3 shows the IFC schema extension for sizing reactors, building upon the WWTP IFC extension proposed in Söbke et al. (2018). The extract shown in Figure 3 describes an IFC submodel, referred to as IfcProcessSpaceLoadModel, developed following the concept implemented in the IFC entity IfcStructuralAnalysisModel of the current IFC schema. Because of the analogy of the sub model and the existing IFC entity, ease of use is expected for users familiar with the entity IfcStructuralAnalysisModel. The IFC schema extension for sizing reactors extends the
submodel $\text{IfcProcessSpaceLoadModel}$ by creating new enumeration values for $\text{IfcProcessSpaceLoadTypeEnum}$ for sizing design methods and new IFC subentities of $\text{IfcProcessSpaceLoad}$ to describe load cases defined by each design method and of $\text{IfcProcessSpaceResult}$ to describe the resulting variants for each sizing design method.

The IFC schema extension for sizing reactors is implemented for one type of anaerobic digestion reactor with standard operating conditions. Figure 4 shows the entities of the IFC schema extension for sizing an anaerobic digestion reactor in biogas plants. The entities $\text{IfcProcessSpaceLoad}$ and $\text{IfcProcessSpaceResults}$ are defined according to the semantic model shown in Figure 2, where the configuration and input parameters are defined as process space loads, and the output parameters are defined as process space results. In the IFC schema extension for sizing reactors, the operational, input, and output parameters are described either with enumeration values or with double data types. Due to specific parameter types, new subentities of $\text{IfcResourceMeasure}$, such as $\text{IfcMassVolumetricFlowRateMeasure}$ and $\text{IfcDensityMassMeasure}$, are introduced.

The IFC schema extension introduced herein provides a procedure to formalize sizing of reactors supporting BIM-based planning of processing facilities, while minimizing the complexity of future IFC schema extensions, thus reducing the time required for standardization processes, which usually take up to five years. One example of efforts at making the standardization process in a reasonable time is the IFC scheme extension $\text{IFC Bridge}$, which
was carried through in the fast-track (Borrmann, et al., 2019). The fast-track approach does not claim to cover all conceivable details, but rather to focus on frequently occurring manifestations of properties and entities. Therefore, with the concept of the ProcessSpaceLoadModel, a data model equipped with the specialized subclasses for reactors may be standardized in shorter times. In the following section, the IFC schema extension is validated with an illustrative example.

4. Validation of the IFC schema extension for sizing reactors

To validate the IFC schema extension for sizing reactors, an IFC-compliant BIM model of an anaerobic digestion reactor is modelled (i.e., instantiated) from the IFC schema extension, as shown in Figure 5, to describe its sizing information. The reactor is first modeled using a BIM tool and then the corresponding IFC file is generated. Next, the IFC file is processed using a Java-based software application, capable of reading and editing IFC files, which incorporates the IFC schema extension. The Java-based software application extends the IFC file to incorporate the entity IfcProcessSpaceLoadModel, which describes the sizing information. Listing 1 shows an extract of the processed IFC file covering load and sizing results data for the anaerobic digestion reactor; the semantics of the attributes are annotated.

Figure 4: IFC schema extension for sizing anaerobic digestion reactors in biogas plants.
Figure 5: BIM model of the anaerobic digestion reactor.

Listing 1: Extract of the IFC file of the anaerobic digestion reactor, specifying load and sizing result data using the IfcProcessSpaceLoadADR and IfcProcessSpaceResultADR entities.

5. Summary and conclusions

Enabling BIM-based planning of processing facilities, an IFC schema extension supporting sizing of reactors, a crucial task in planning processing facilities, has been presented. The IFC schema extension, designed in compliance with the current IFC schema, has exemplarily been illuminated by means of anaerobic digestion reactors in biogas plants. As a result, planning processing facilities is advanced through enhanced data exchange between planners while reducing errors and costs. The IFC schema extension has been implemented as a generic approach that may be applied to sizing of further types of reactors with other input and output parameters. As has been demonstrated in the validation of the IFC schema extension, the extension may be used as basis for BIM-based simulations of process facilities.
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