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# MVD based Information Exchange between BIM and Building Energy Performance Simulation

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## Abstract

The process of preparing Building Energy Performance Simulation (BEPS) models involves repetitive manual operations that often lead to data losses and errors. As a result, BEPS model inputs can vary widely from this time consuming, non-standardised and subjective process. This paper proposes a standardised method of information exchange between Building Information Modelling (BIM) and BEPS tools using the Information Delivery Manual (IDM) and Model View Definition (MVD) methodologies. The methodology leverages a collection of use cases to initiate the identification of exchange requirements needed by BEPS tools. The IDM/MVD framework captures and translates exchange requirements into the Industry Foundation Classes (IFC) schema. The suggested approach aims to facilitate the transfer of information from IFC based BIM to either conventional or advanced BEPS tools (e.g. EnergyPlus or Modelica) through the development of a specific MVD that defines a subset of the IFC data model that deals with building energy performance simulation. By doing so, the potential of BIM-based simulation can be fully unlocked, and a reliable

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and consistent IFC subset is provided as an input for energy simulation software.

*Keywords:* BIM, IFC, BEPS, HVAC, MVD, Information Exchange.

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## 1. Introduction

Building Energy Performance Simulations (BEPS) models are an integral part of the design process for energy efficient and high-performance buildings. Through expert use of BEPS tools and models significantly assist investigation of design options and assess the environmental and energy impacts of design decisions [1]. However, the challenge when designing high performance buildings demands a paradigm change in the way information is exchanged in the building industry. Traditionally, most building design related information is poorly documented and communicated across the entire building life-cycle [2, 3]. Under these circumstances, information exchange often leads to data fragmentation and poor data quality. The preparation of inputs for BEPSs heavily depends on the information that is created and communicated across the building life-cycle. Consequently, when using an incomplete and unreliable set of information, BEPS is in general arbitrary and cannot be trusted [4].

According to [5], there are two types of BEPS: conventional and advanced. Conventional building simulation programs formulate models using programming languages that assign values to functions, declare the sequence of execution of these functions and change the state of the program. In such programs, equations are tightly intertwined with numerical solutions methods, often by making the numerical solution procedure part of the actual model equations. On the other hand, advanced simulation tools are based on object-oriented languages and equation-based modelling. The key advantage is that equation-based languages do not require specific sequence of computer assignments when simulating a model. This method allows software to analyse and make use of the structure of the equations in order to generate efficient code for computation.

It is important to notice that a large portion of data required by both BEPS is the same, regardless of whether one uses conventional (with EnergyPlus),

28 advanced (Modelica libraries) or mixed tools (co-simulation). By recognising  
 29 the differences between conventional and advanced BEPS tools it is possible  
 30 to affirm that each application requires certain types of data and therefore  
 31 has different exchange requirements. For a successful exchange process it is  
 32 necessary to identify the different types of information required by both BEPS  
 33 tool types and be able to exchange relevant data. The approach taken in this  
 34 paper does not consider individual tools but rather the types of information  
 35 that either application uses.

36 Independently of the BEPS software used to conduct an energy simulation,  
 37 the typical process of preparing a model involves repetitive manual operations  
 38 that often lead to duplication of existing data, data losses and errors [6]. Out-  
 39 comes from this non-standardised process can widely vary from modeller to  
 40 modeller, even given the same initial building design information [7]. In order  
 41 to improve the method of information exchange in the Architecture, Engineer-  
 42 ing, Construction and Facility Management (AEC/FM) industry, recent efforts  
 43 have concentrated on integrating Building Information Modelling (BIM) with  
 44 BEPS tools [8, 1, 9, 10]. Such integration can completely change how informa-  
 45 tion is exchanged between both domains by taking advantage of the information  
 46 that is created and stored within BIM. Usually, more than 70% of the informa-  
 47 tion needed by energy simulation tools has already been stored within a BIM,  
 48 which greatly reduces the time necessary to gather information from different  
 49 sources [11].

50 BIM applications can generate several data exchange formats to share in-  
 51 formation. The most common are: Industry Foundation Classes (IFC) and  
 52 Green Building XML (gbXML). Both have valuable features [12] but IFC was  
 53 chosen because of its wider scope in comparison to gbXML and for the fact  
 54 that gbXML uses centre line representation for geometry. This convention has  
 55 shown to result in calculated surface areas and space volumes differences which  
 56 significantly exceed the standard engineering tolerance causing over estimation  
 57 of building energy consumption [13]. IFC is the only life-cycle BIM data format  
 58 that is an international standard, which is defined in the ISO 16739 [14]. IFC is

59 an open data format fully extensible and neutral, and is the most suitable open  
60 format to exchange information between different software applications across  
61 the entire building life-cycle [15].

62 A fully populated BIM can result in an enormous model, typically too large  
63 for any stakeholder specific software application [4]. For this reason, buildingS-  
64 MART International (previously known as the International Alliance for Inter-  
65 operability (IAI)) developed the Model View Definition (MVD) methodology  
66 to act as a filter and reduce the size of models accordingly to specific business  
67 processes [16]. This method potentially encapsulates all information related to  
68 a specific process or set of processes in a comprehensive subset of the overall  
69 data schema and facilitates sharing of pertinent information between BIM and  
70 other tools such as BEPS.

71 The work presented in this paper reflects the results of the German EnEff:BIM-  
72 Project [17, 18, 19, 20] which is part of The International Energy Agency Energy  
73 in Buildings and Communities (IEA EBC) Annex 60, Activity 1.3. The Annex  
74 60 project provides new methods for the integration of BIM and advanced BEPS  
75 tools [21]. The paper aims to facilitate the transfer of information from IFC  
76 based BIM to either conventional or advanced BEPS tools (e.g. EnergyPlus or  
77 Modelica) through the development of a specific MVD that defines a subset of  
78 the IFC data model that deals with building energy performance simulation.  
79 In doing so, the potential of BIM-based simulations can be fully unlocked, and  
80 a reliable and consistent IFC subset provided as an input for BEPS software.  
81 This paper is structured as follows: Section 2 details a review of existing energy  
82 related MVDs. Section 3 presents an overview of Annex 60 project and the need  
83 for a specific MVD for BEPS tools. Section 4 explains the methodology and  
84 describes the use cases applied for developing the MVD. Section 5 summarises  
85 the difficulties and limitations encountered during the project. Finally, Section  
86 6 concludes the work presenting the primary findings and the next steps for this  
87 research.

## 88 2. Background

89 Energy modelling using BIM has the potential to simplify the process of  
90 model generation by seamlessly leveraging the necessary information stored in  
91 an architectural or mechanical BIM. IFC is one such extensible data model  
92 which conceptually describes the information required by all project stakehold-  
93 ers across the entire building life-cycle. IFC provides static building information  
94 that includes geometry configurations and material properties. The format is  
95 an object-oriented international standard developed by buildingSMART and  
96 has the ability to represent elements of a building as objects with objectified  
97 relationships to other objects. Furthermore, IFC permits a definition of domain  
98 specific subsets to support a user defined process or processes (e.g. cost estima-  
99 tion or BEPS). According to [22], IFC has been in development since 1994 and  
100 has subsequently evolved through contributions of research and industry (Figure  
101 1). IFC 2.0 was the first truly international release and was primarily focused  
102 on building services, cost estimation and construction planning. In 2005, IFC2x  
103 attained the ISO/PAS 16739 status and a significant push for IFC-based BIM  
104 was initiated. Beginning of 2006 the IFC2x3 was released and the IDM (In-  
105 formation Delivery Manual) and MVD were introduced as standard approach  
106 for IFC implementation. The IDM provides a split framework for definition of  
107 exchange requirements and contains two parts: the first consists of components  
108 for defining the processes undertaken by actors and the exchange requirements  
109 associated with these processes, and the second takes the interfaces between dif-  
110 ferent software applications into account and is IFC schema dependant. Both  
111 parts are crucial for guiding the workflow of IFC enabled exchanges and to  
112 document how data exchanges are applied between different application types.

113 The Coordination View was the first official MVD released by buildingS-  
114 MART and is extensively implemented in most of the commercially available  
115 BIM applications (based on IFC2x2 and later IFC2x3). It was developed to  
116 support sharing of building models between the major disciplines of architec-  
117 ture, structural and mechanical engineering [23]. In 2015, buildingSMART re-

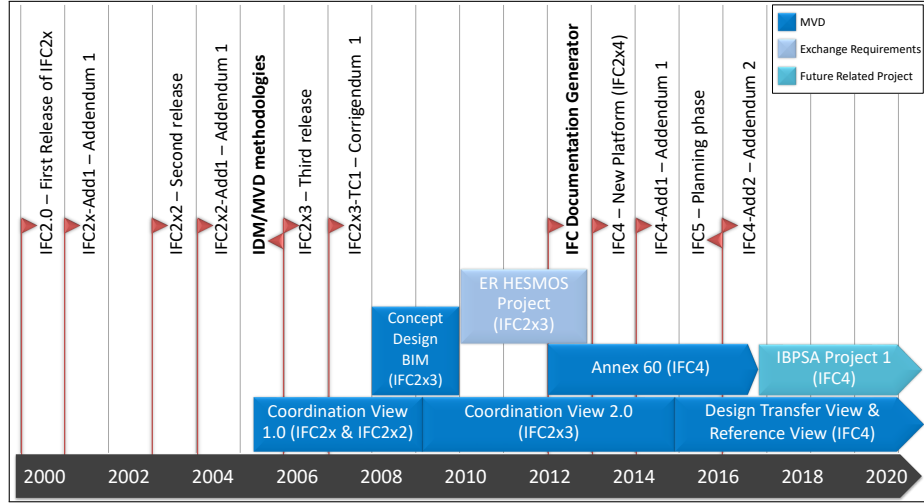


Figure 1: Summary of the IFC releases with key enabling technologies for IFC implementation together with MVD development over the years.

leased the latest version of the IFC schema, IFC4, which brought significant improvements in: i) energy and performance analysis, ii) environmental impacts values, iii) integration of ifcXML and mvdXML into specification and iv) improved documentation [24]. In order to support IFC4 implementation, buildingSMART released two new model views: Reference View (RV) and Design Transfer View (DTV). RV is a subset of DTV with the main purpose of supporting the exchange in one direction only [25], while DTV main purpose is to promote collaboration between multiple disciplines. DTV is considered the successor of the IFC2x3 Coordination View and is intended to be compatible with IFC2x3 import [26]. According to [27], a new version (IFC5) is in early planning phase and is intended to include full support for various infrastructure domains and additional parametric capabilities.

### 2.1. Review of Energy Related MVDs

Since the introduction of the MVD concept, organisations started developing their own MVDs to support internal processes based on the IFC schema (Figure 1). Developments in the area of energy performance include: Concept

134 Design BIM 2010 (CDB) [28] and Holistic Energy Efficiency Simulation and  
 135 Management of Public Use Facilities (HESMOS) [29]. The CDB project de-  
 136 veloped an MVD focused on a general definition of energy analysis with the  
 137 purpose of supporting the coordination of energy analysis requirements with  
 138 general zoning and spacing requirements. The areas covered in this exchange  
 139 include: building structure (e.g. location, composition, orientation, etc.), space  
 140 type and function identification (e.g. internal loads, conditioning requirements,  
 141 etc.), building elements construction (e.g. thermal characteristics and internal  
 142 constructions), space boundaries (e.g. 2<sup>nd</sup> level space boundary), HVAC zoning,  
 143 daylighting and use of photovoltaic equipment.

144 The HESMOS project did not define an MVD but instead, the project fo-  
 145 cused on the definition of exchange requirements for energy analysis representing  
 146 the last step before being able to develop an MVD (in a top-down-approach).  
 147 The main areas covered by the project are: building structure (e.g. geometry,  
 148 2<sup>nd</sup> level space boundaries, etc.), energy-related technical equipment (e.g. in-  
 149 ternal loads for example heat gains caused by technical equipment, etc.), space-  
 150 related user behaviour (e.g. set point temperatures, metabolic rate, etc.) and  
 151 site data (e.g. geographical position, location, etc.). At the time of the HESMOS  
 152 project, all IFC files contained 1<sup>st</sup> level space boundaries only. Consequently  
 153 and for the purposes of BEPS, an additional process that added 2<sup>nd</sup> level space  
 154 boundaries using a conversion tool was required [30]. With the 1<sup>st</sup> level space  
 155 boundaries, HESMOS accounted for most of the relevant data required for a  
 156 static energy simulation but was insufficient for a dynamic energy simulation.  
 157 Figure 2 shows a comparison of the contexts covered and the number of exchange  
 158 requirements defined in each MVD.

159 In conclusion, CDB and HESMOS primarily focus on building envelope with  
 160 only minor attention given to the exchange of HVAC related data. As a result,  
 161 the information defined in each project is insufficient to conduct a BEPS but it  
 162 is a valid starting point. Thus, the Annex 60 MVD combines the information  
 163 from both projects, and adds more information related to HVAC components,  
 164 where appropriate, as a second step towards an MVD for BEPS.



<i>Context Covered</i>	<i>HESMOS</i>	<i>CDB</i>	<i>Annex 60</i>	<i>Maximum of ER</i>
Project	0	8	26	27
Building	7	10	41	53
Building Story	0	1	18	18
Spaces	56	88	267	283
HVAC equipment	51	14	436	459
Renewable ressources	8	6	0	13
Total of exchange requirements	122	127	788	853
Percentage of the total	14.30%	14.89%	92.38%	100.00%

Figure 2: Comparison of the contexts covered and the number of exchange requirements defined in each energy related MVD. Maximum ER represents the union of all requirements of each MVD with no duplication.

### 3. Information Exchange Process to Support BEPS

The IEA EBC Annex 60 project promotes research and development of new methods to help design and operate energy efficient buildings and communities [21]. Activity 1.3 of the Annex 60 focuses on the complex issue of transforming a digital model of a building and its HVAC systems into semi-automatically generated Modelica code that can be readily used for advanced BEPS models. The main objective of this activity is to address the prevailing tedious, cumbersome and error-prone process of manual data conversion and model generation by providing a semi-automatic method of data transformation.

The process from BIM to BEPS tools involves three main actors: the architect, the HVAC engineer and the energy specialist (Figure 3). The process starts with the architect, who prepares the geometry model using a BIM authoring tool (e.g. Autodesk Revit, ArchiCAD, Tekla, etc.). It is important to note that BEPS tools require a much simpler building geometry representation than Computer Aided Design (CAD) programs [31, 32]. For this reason, building geometry representation must be prepared (i.e. simplified, reduced, translated or interpreted) before it can be used by BEPS tools [33]. The preparation or simplification can be done automatically to some extent but also needs manual efforts. Once the building design concept is complete with all the required

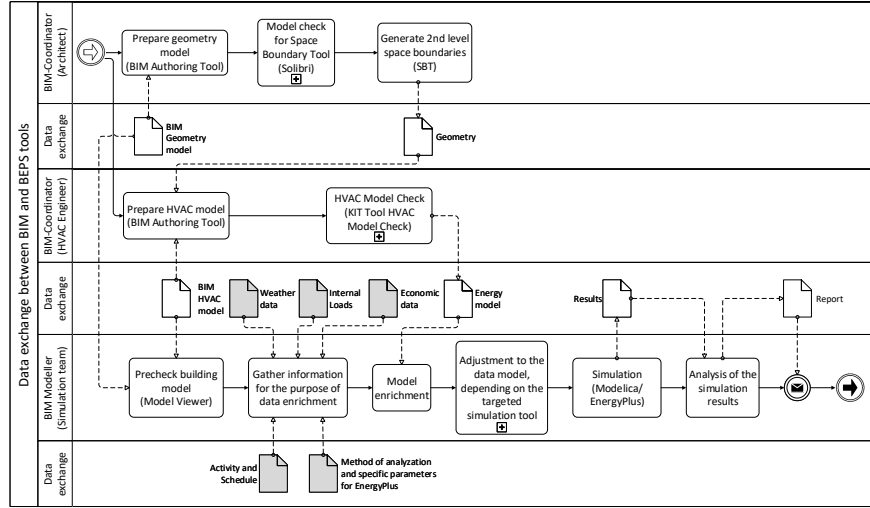


Figure 3: Process map for the exchange of information between BIM and BEPS engines, Modelica and/or EnergyPlus.

building elements and space objects, it is exported as an IFC data model in  
 accordance with the MVD defined in the project to support energy analysis  
 (Section 4.1). The IFC file passes through a  $2^{nd}$  level space boundary model  
 checker (e.g. Solibri Model Checker) to assure that major modelling errors have  
 been removed [34]. Space boundaries are defined as a system of surfaces that  
 delineate walls, slabs, roofs, columns, beams, windows and doors [35]. Such  
 spaces are a critical part of the building geometry representation that is nec-  
 essary for BEPS. In cases where space boundaries are missing from the model,  
 the Space Boundary Tool (SBT) can be used to generate the  $2^{nd}$  level space  
 boundaries [36].

Based on the geometry model of the building created by the architect, the  
 HVAC engineer adds information about HVAC systems. At this point, the  
 engineer uses static/conservative dimension methods to specify systems com-  
 ponents and parameters. Quality assurance is an important precondition for a  
 qualified simulation process. Thus, it is necessary to have a coherency check  
 of the IFC file to ensure that modelling requirements are satisfied. Based on  
 the requirements in the MVD, specific rules were defined using the KIT tool,

201 HVAC Model Checker [37], to check whether a designated model is compliant  
202 with these requirements or not [38].

203 After successful completion of the rule checking process, the engineer can  
204 generate an IFC file that is in turn used for BEPS. This file contains both  
205 geometry and HVAC system definitions. At this point, the energy specialist  
206 checks the IFC file for its completeness, consistency and validity. During the  
207 checking process, any missing information required for energy simulation can  
208 either be added, transformed, simplified or requested [33]. Additionally, the  
209 energy specialist gathers additional information such as weather data, economic  
210 data, etc., and enhances the model specifically for the targeted simulation tool.  
211 Even though, the process of information exchange was described as a sequen-  
212 tial method, it is important to note that modern processes are becoming more  
213 collaborative. Collaborative environments allow for inclusion of different actors  
214 in the early stages of the project, leading to an effective exchange of informa-  
215 tion between disciplines and ensuring that the necessary set of information is  
216 included in the model. By taking this approach, the semi-automated process  
217 creates a reliable and consistent IFC data model that captures all the relevant in-  
218 formation needed to support the target BEPS tool. Under these circumstances,  
219 a successful exchange between BIM and BEPS tools can only be achieved if  
220 the MVD incorporates the required subset of the target domain in a format  
221 consistent with the BIM schema.

## 222 4. Methodology

223 The approach taken in this paper uses a set of use cases to initiate identifica-  
224 tion of exchange requirements needed by BEPS tools. The MVD was developed  
225 using a bottom-up approach based on defined use cases that enabled control over  
226 the export to IFC. The core process of the development captures energy sim-  
227 ulation domain knowledge and translates this knowledge into the IFC schema  
228 using the IDM/MVD methodology (Figure 4). This approach focused on the  
229 latest release of the IFC schema, IFC4 Addendum 2 (IFC4 Add2), in order to

230 identify what information can be used from the schema. An in-depth analysis  
 231 of the content of IFC4 Add2 showed that most of the information needed by  
 232 energy simulation is already defined in the schema. However, some additional  
 233 definitions related to schedules and internal loads had to be created (Section  
 234 4.1).

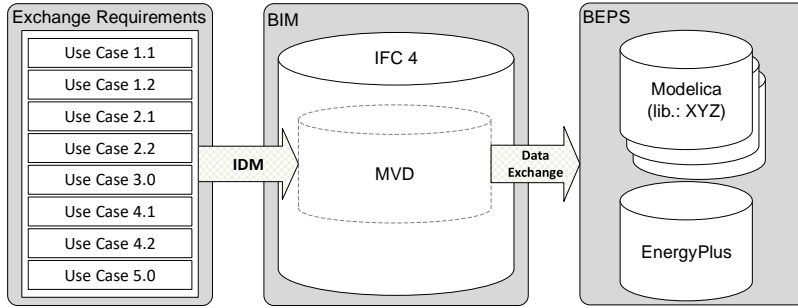


Figure 4: Methodology diagram for definition of the MVD using a collection of use cases to extract the information needed by BEPS tools.

235 The use cases vary in levels of complexity from a single room to a large com-  
 236 mercial building resulting to a total of eight use cases (Figure 5). Such variation  
 237 ensures that different components with multiple model topologies are considered  
 238 along with the definitions of necessary content for the exchange. A single room  
 239 was parameterised according to the German guideline VDI 6007-1 and used in  
 240 use cases 1.1 - 4.2 (Figure 6(a)). Internal loads for people, plug loads and lights  
 241 are taken from DIN V 18599-10 and SIA 2024 (Standard-Nutzungsbedingungen  
 242 für Energie und Gebäudetechnik) standards [39, 40]. Use case 5.0 is a multi-zone  
 243 three story office building that comprises office spaces, kitchens, washrooms,  
 244 corridors and a mechanical room. This use case was included to illustrate the  
 245 BEPS and data modelling challenges associated with a large scale engineering  
 246 project (Figure 6(b)).

247 Autodesk Revit 2016 was used to model all use cases. Revit permits the user  
 248 to model both the building geometry (Revit Architecture) and the Mechanical  
 249 Electrical and Plumbing (MEP) systems in the same work environment. For  
 250 walls, the ceiling and floor, each material layer was defined, including physi-

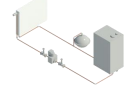
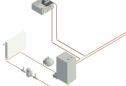
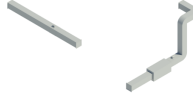
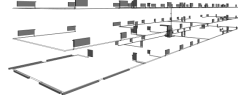
<i>Identifier and Name</i>	<i>HVAC System (generation + emission)</i>	<i>Revit Model</i>
1.1 Boiler	Gas boiler and radiator	
1.2 Boiler	Gas boiler, buffer storage for domestic hot water and radiator	
2.1 Heat Pump	Heat pump, buffer storage and radiator	Missing IFC entity to represent the heat pump
2.2 Heat Pump	Heat pump and floor heating	Missing IFC entity to represent the heat pump
3.0 Combined Heat and Power (CHP)	CHP unit and radiator	Missing IFC entity to represent the CHP unit
4.1 and 4.2 Air Handling Unit (AHU)	AHU Heating (4.1) and Cooling (4.2)	
5.0 Multi Zone	1.1 Boiler	

Figure 5: Overview of the use cases definition describing the main components of the HVAC system for each use case.

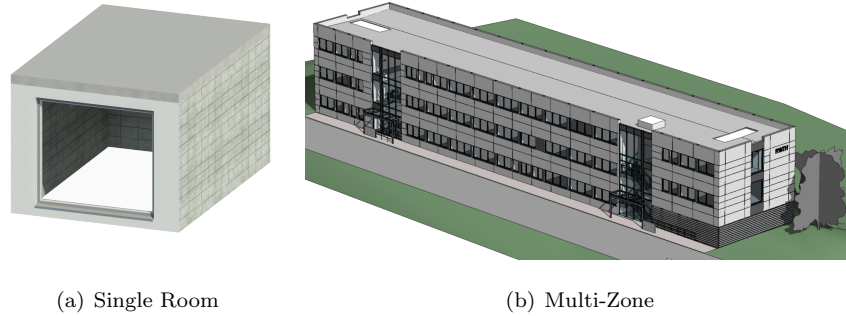


Figure 6: (a) Single room parametrisation according to German guideline VDI 6007-1 applied to use cases 1.1 - 4.2. (b) Multi-zone office building used in use case 5.0.

251 cal characteristics such as density ( $\text{kg/m}^3$ ), thermal conductivity ( $\text{W/m}\cdot\text{K}$ ) and  
252 thickness (m), as well as specific details for windows. For the HVAC system,  
253 the MEP model included dimensions for all components and data concerning

254 component placement. Correct HVAC system typology was also a key require-  
255 ment. The modelling process helped the authors to identify the capabilities of  
256 BIM applications regarding the definition of exchange requirements specific for  
257 energy simulation.

#### 258 4.1. Annex 60 MVD

259 The Annex 60 MVD focuses on the definition of a subset of the IFC build-  
260 ing product model that encapsulate entities, attributes, relations and properties  
261 that support BEPS tools. The IDM/MVD also defines the business rules and  
262 agreements that are outside of the scope of the MVD definition which are nec-  
263 essary to assist implementation of export functions by BIM applications.

264 The MVD is composed of the following elements:

- 265 • *ModelView*
- 266 • *ConceptRoots*
- 267 • *ExchangeRequirements*
- 268 • *ConceptTemplates*
- 269 • *and Concepts*

270 *ModelView* is the description of an MVD and is specific to an IFC schema re-  
271 lease. In doing so, *ModelView* groups zero-to-many *ExchangeRequirements* and  
272 *ConceptRoots*, thereby defining the scope of the MVD. The *ExchangeRequire-*  
273 *ments* define the information necessary for a particular exchange scenario and  
274 may include additional constraints for existing *Concepts*. The *ConceptRoot* is  
275 represented by a collection of available *Concepts*, each of which references a  
276 specific IFC entity (e.g. *IfcSpace*). Each *Concept* describes rules for common  
277 subsets of information (e.g. space attributes) within the context of the par-  
278 ticular *ConceptRoot*. The *Concept* is supported by a *ConceptTemplate* which  
279 describes a graph of object instances, relationships and constraints. The infor-  
280 mation contained inside the *ConceptTemplate* enables the generation of MVD

instance diagrams [41]. The fundamental components for a BEPS related MVD  
are shown in Figure 7, each of which is now detailed.

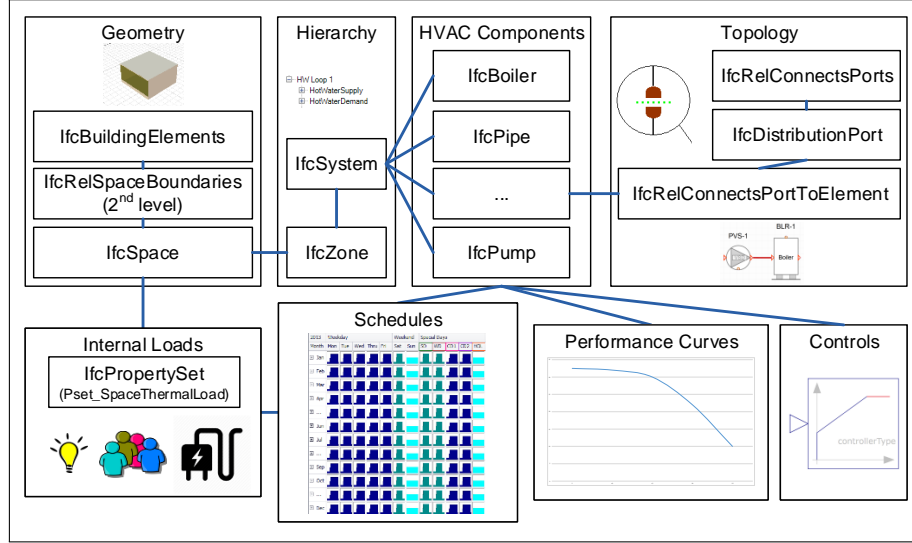


Figure 7: High level overview for the Building Energy Performance Simulation MVD.

The accuracy of a BEPS model depends significantly on the correct representation of building *Geometry*. As a result, geometrical definitions should include material data such as thermal properties and thicknesses; construction layers and all types of 2<sup>nd</sup> level space boundaries which link spaces to building components.

*Internal Loads* are any sensible and latent heat emitted within a space from any source. The most common sources are: occupants, lighting and equipment. IFC4 already has designated properties for internal loads such as: maximal/minimum temperature of the space; maximum number of people; total sensible heat or energy gained; lighting loads and percent of sensible load to radiant heat. However, the dynamic temporal nature of schedules is still missing and this is a crucial requirement for BEPS.

The ability to define complex *Schedules* in conjunction with previously defined properties for internal loads enables a definition of detailed time-dependant internal loads. To date, this schedule requirement has not been introduced by

any other discipline. Using IFC4, schedules can be defined in three different ways:

- 'IfcWorkCalendar': On/Off status through the year with predefined patterns;
- 'IfcRegularTimeSeries': A regular time-series that defines values based on a regular time interval (e.g. hourly);
- 'IfcIrregularTimeSeries': A time series that defines values on an irregular time-series (e.g. set of data at unspecified points in time).

Typically, BEPS schedules follow a regular uniform time-unit format such as hourly, daily, weekly and seasonal patterns. The ability to define patterns significantly simplifies and reduces the data representation of schedules. In the latest release of the IFC4 schema, 'IfcWorkCalendar' uses the 'IfcRecurrencePattern' to define such patterns, but can only contain an on/off signal. This configuration can be used to represent a certain quantity of people in the thermal zone on a weekday, which changes over the course of the day, however, the opening range of a valve on a national holiday cannot be described with a boolean flag. This is a significant limitation of the IFC model and creates the need for a workaround solution.

In order to overcome this limitation, a new concept was defined for the MVD. The top level of the concept hierarchy is 'IfcObject' as this entity is best suited for applying schedules to any semantically treated object or process. The spatial element is assigned to 'IfcPerformanceHistory' via a relationship ('IfcRelAssignsToControl') and 'IfcPerformanceHistory' offers the recurrence patterns using the entity 'IfcWorkCalendar'. 'IfcPerformanceHistory' is also defined by properties, which in turn allow the definition of complex properties and regular/irregular time-series. The application of the new concept enables a representation of detailed schedules for entities that can be scheduled (e.g. occupancy in thermal zones) (Figure 8).



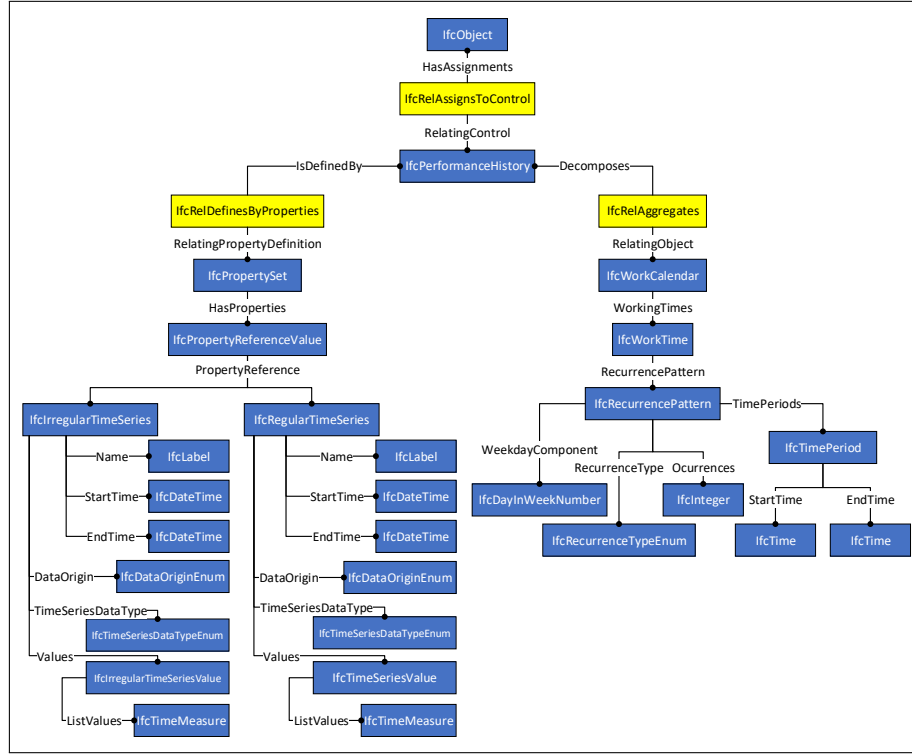


Figure 8: Structure of the MVD concept developed for representing schedules definition on energy simulation.

326 The *Hierarchy* for the thermal zones are defined using the 'Object Com-  
 327 position' concept template. Two options are available at this level: i) Spatial  
 328 Composition and ii) Spatial Decomposition. Both define a hierarchical tree of  
 329 spatial elements ultimately assigned to the project. While Spatial Composi-  
 330 tion is used to represent spatial structure elements from a high to a low level  
 331 (e.g. 'IfcProject', 'IfcSite', 'IfcBuilding', 'IfcBuildingStorey', and 'IfcSpace'),  
 332 the Spatial Decomposition can be used in the opposite order from a low to a  
 333 high level. The subtype 'IfcRelAggregates' is used to link the instances and  
 334 establishes a hierarchical structure. 'IfcSpace' is the lowest level in the hierar-  
 335 chy and is a common entity used to provide all information about spaces. An  
 336 important concept used in the development of BEPS models is the capability  
 337 to group thermal zones that behave in similar ways. Within the IFC schema,

the 'IfcZone' entity is defined as a subtype of 'IfcGroup', thus it can be used as a grouping mechanism that aggregates spaces or other zones.

HVAC systems are defined using the 'Aggregation' and 'Group Assignment' concept templates. The former is used to illustrate the relationship of systems and subsystems, while the latter is used to establish an arbitrary collection of objects within a group. Figure 9 depicts an instance diagram of the group assignment concept. The objectified relationship 'IfcRelAssignsToGroup' is used to enable a grouping mechanism via 'IfcGroup' for 'IfcProduct'. For example, 'IfcDistributionSystem' is a specific group object for collecting distribution elements. For a single loop heating system, the distribution system is divided into supply and return subsystems, in which radiators represent a thermal sink and the boiler a thermal source. No previous agreements exist on the system hierarchy, therefore a simple hierarchy with one parent system for each loop is proposed that in turn contains supply and demand subsystems. For simulation purposes, this differentiation helps to identify respective supply and demand components within a given loop.

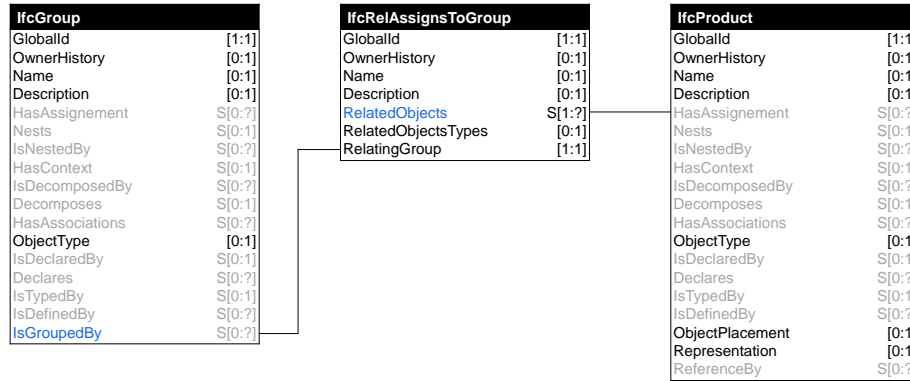


Figure 9: Instance diagram of the Group Assignment Concept used to group HVAC systems. The pipe and the cable segments are not represented.

Several enhancements to *HVAC components* were made in the IFC4 schema. In particular, component definitions became more detailed. For example, an 'IfcBoiler' was previously represented as a generic 'IfcEnergyConversionDevice'.

357 This significant enhancement makes the representation of HVAC components  
 358 more explicit. However, several HVAC components were not upgraded to include  
 359 this additional level of detail, for example, heat pumps and combined heat and  
 360 power units. In such cases, those components need to be represented with a  
 361 more generic class 'IfcUnitaryEquipment' which typically combine a number of  
 362 components into a single product, such as air handlers, pre-packaged rooftop  
 363 air-conditioning units, heat pumps, and split systems.

364 IfcUnitaryEquipment is used to model a heatpump that in-fact combines  
 365 several components including filter, valves, compressor, condenser, evaporator,  
 366 several sensors and actuators, and a control unit (Figure 10). This example  
 367 shows the process of heating exchange between the source (SourceIn), refrigerant  
 368 (CO<sub>2</sub>) and medium (ReturnWater).

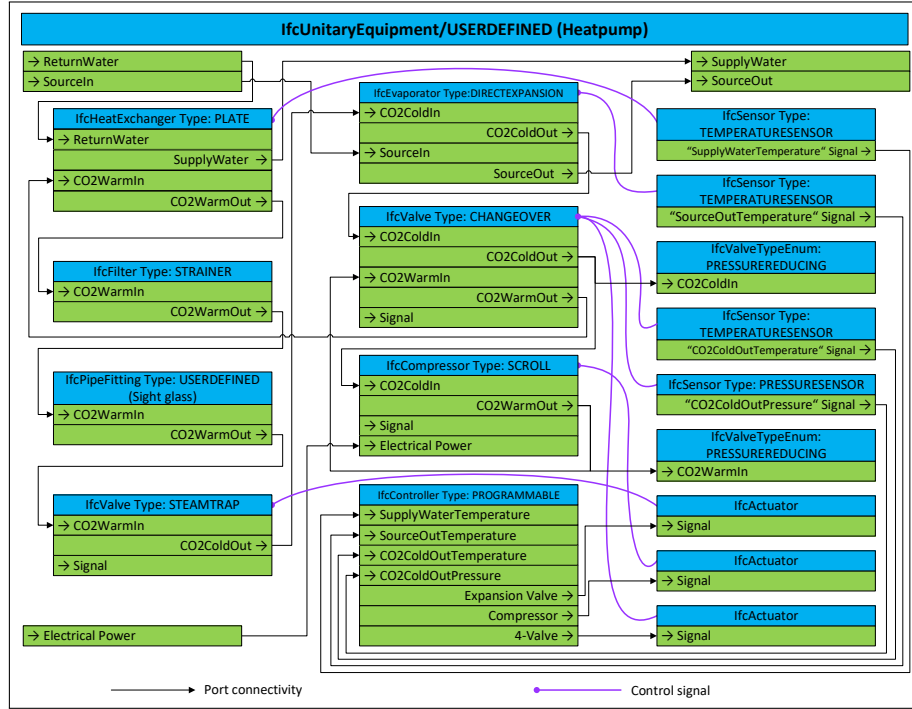


Figure 10: Concept to define a Heatpump entity, using the methodology provided by IfcUnitaryEquipment [42].

369 *Topological* connections are one of the key concepts to consider in the defini-

tion of HVAC systems as most HVAC systems are based on fluid flow. Within IFC, topological relationships are defined by instances of 'IfcDistributionPort', which are in turn connected to 'IfcDistributionElement'. Through the use of this convention, connected ports share the same system type and have opposite flow directions (one side being a source and the other being a sink). The 'IfcRelConnectsPorts' relationship connects the ports and forms the basis for the topology.

*Performance curves* are key features of HVAC equipment. Typically, these curves describe the specific behaviour of a component at varying conditions (e.g. boiler efficiency curve that depends on the water return temperature). This concept type is still missing in IFC4. In order to overcome such limitations, the 'IfcComplexProperty' was used to nest 'IfcProperty' subtypes. This approach in turn provides a mechanism where a set of properties are included as a single property entry in an 'IfcPropertySet' [43].

*Controls* manages, commands or regulates behaviour of HVAC components. IFC schema provides the 'IfcControl' entity since release 1.0, however, when working with BIM applications, control parameters required by BEPS are not rigorously implemented. For this reason, user defined property sets were created and attached to components to emulate the effects of control strategies.

Overall 49 additional properties were defined and added to existing objects to support the data exchange between BIM and BEPS tools (Figure 11). The missing properties were identified by analysing how the HVAC components are modelled in EnergyPlus version 8.2 and two Modelica libraries (AixLib from Aachen and BuildingSystems from UdK Berlin), and comparing the objects to the existing IFC4 properties set definition for the corresponding object. The missing properties were introduced to overcome the lack of information needed for BEPS. Such processes require a comprehensive analysis of the given entities, property sets and data types of the IFC4 data model. Additional properties were developed for eight different HVAC components (IfcBoiler, IfcCoil, IfcDuctSegment, IfcFan, IfcPump, IfcSpaceHeater, IfcController, IfcValve), as well as, for the building envelope (IfcWindow and IfcMaterial) to provide relevant data.

401 Additionally, Modelica demands very specific input data to simulate internal  
 402 loads, hence, eight additional properties were defined and assigned to 'IfcSpace'  
 403 entity.

Property Name	Property	Property Name	Property
PSim_Valve	NominalMassFlowRate	PSim_Fan	NominalMassFlowRate
	NominalPressureDrop		MaxMassFlowRate
PSim_DuctSegment	HydraulicDiameter	PSim_SpaceHeater	NominalMassFlowRate
	ReynoldsNumber		NominalInletTemperature
	NominalMassFlowRate		NominalOutletTemperature
	NominalPressureDrop		RatedAverageWaterTemperature
	OverallHeatTransCoeUFactorFromAirToAir		MaxWaterFlowRate
PSim_Window	OverallMoistTransCoeFFromAirToAir		RadiantFraction
	TransmissionCoefficient	PSim_Material	CoefficientOfHeatTransfer
	TransmissionCoefficientShading		Emissivity
PSim_Space	RadiantEnergyFluenceRateShading	PSim_ControllerPID	AbsorptionCoefficient
	NumberOfPeopleWithMachines		Setpoint
	RatioConvectiveHeatMachines		IntegrativeTimeConstant
	RatioConvectiveHeatPeople		DerivativeTimeConstant
	RatioConvectiveHeatLights		LimitOfPIDOutput
	MaxUserACH		WeightP
	MaxOverheatingACH		WeightD
	MaxSummerACH		ControllerVariable
PSim_Boiler	WinterReductionACH		ControllerType
	DesignWaterFlowRate	PSim_Pump	FractionOfMotorInefficienciesToFluidStream
	ParasiticElectricLoad		ControlType
	NominalMassFlowRate		SkinLossRadiativeFraction
Qsim_BuildingQuantities	PLREfficiency		HeadMax
	LengthLongerSide	PSim_Coil	NominalMassFlowRate
	WidthSmallerSide		NominalMassFlowRate
	NumberOfStories		NominalCapacity

Figure 11: Properties set definitions to support the data exchange between BIM and BEPS tools.

404 The definition of property sets describe how sets of properties (usually de-  
 405 fined by a name, value, unit triple) are associated to objects or object types [43]  
 406 (Figure 12). In addition to the properties, 'Quantity Sets' are defined to pro-  
 407 vide necessary information. Quantity sets function are derived measures of an  
 408 element's physical property. These elements could be spatial structure elements  
 409 or building elements [43]. Additional Quantity Sets are defined for 'IfcBuilding'  
 410 in order to extract information such as the length of the shorter or longer side  
 411 of the building and number of stories.

#### 412 4.2. IFC Documentation Generator (IfcDoc)

413 The IFC Documentation Generator (IfcDoc) is a free tool developed by build-  
 414 ingSMART with the primary purpose of facilitating the documentation of an  
 415 IFC MVD through diagram generation, schema definition and specification of

Property Set	Applicability	Property	Documentation	Property Type	Primary Data Type
Psim_Boiler	Entity: IfcBoiler Predefined Type: Water	PLR Efficiency	Boiler Efficiency Curve $= C1 + C2(PLR) + C3(PLR)^2 + C4(Twater) + C5(Twater)^2 + C6(PLR)(Twater) + C7(PLR)^3 + C8(Twater)^3 + C9(PLR)^2(Twater) + C10(PLR)(Twater)^2$ <ul style="list-style-type: none"> <li>• PLR = Part Load Ratio</li> <li>• Twater = Inlet Water Temperature</li> <li>• The values are stored in a Set of IfcPropertySingleValue using HasProperties in the following order: C1 ... C10.</li> <li>• The boundary conditions for the performance curve are stored in the same Set after the coefficients in the following order: MinimumX, MaximumX, MinimumY, MaximumY, MinimumOutput, MaximumOutput</li> </ul>	Complex	IfcReal
Psim_Controller	Entity: IfcController Predefined Type: Proportional	Limit of PID Output	Modelica parameter: Limit output of the PID controller	Bounded Value Upper: IfcReal Lower: IfcReal	IfcReal

Figure 12: Examples of property set definitions for representation of boiler efficiency curve and controller output of the PID control.

indices and contents of user-defined specifications [44]. This tool also provides limited validation of MVDs and ensures consistent and computer interpretable definitions via mvdXML export functionality [45]. According to [41], the tool uses mvdXML language to: i) support automated validation of IFC data sets for quality assurance and software certification; ii) generate documentation for specific model views and IFC specification; iii) support software vendors that provide filtering of IFC data based on model views; and iv) limit the scope of IFC to well-defined subsets applicable for particular applications.

In order to start the process of defining an MVD, the user must first load a baseline file into the IfcDoc interface [46]. The baseline file contains the full computer interpretable IFC schema specification (including all documentation) and a pre-selected set of reusable MVD concept definitions (Figure 13). To use this tool, the data modeller requires an in-depth understanding of the IFC schema in order to identify semantic classes needed to distinguish the different meanings and related issues in model exchanges. In a model view, specific data requirements can be included and these definitions should explicitly state which data exchange elements are obligatory for an accompanying range of applicable values. The IfcDoc tool is in constant development by buildingSMART and this work contributed to its improvement by giving feedback to developers on the

435 usability and other subjects.

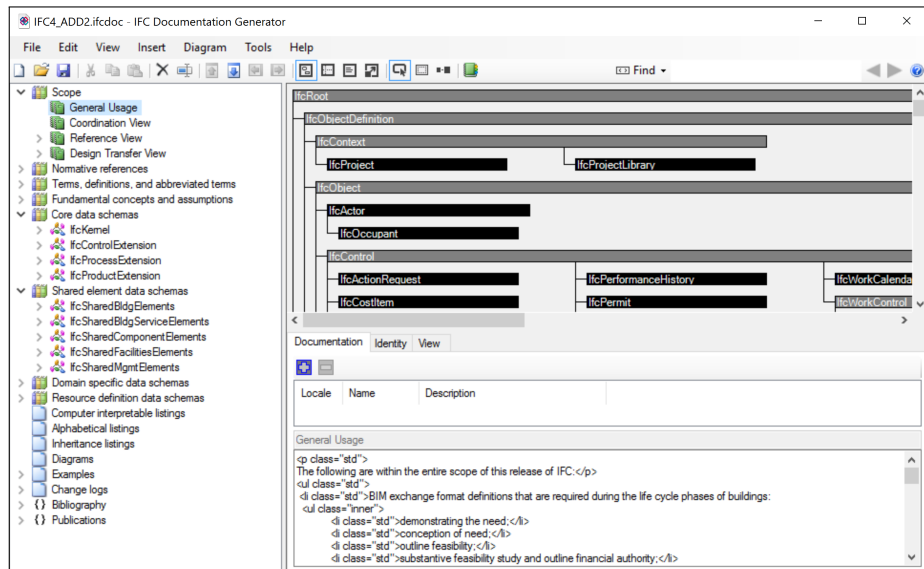


Figure 13: The user interface of IfcDoc tool loaded with baseline file.

436 The IfcDoc tool allows users to define rules for specific entities and attributes  
 437 including the capability to define rules and parameters pertaining to a structure  
 438 and a constraint [47]. Overall, these rules significantly assist with the delivery  
 439 of high quality IFC files. This ruled process ensures that for a specific exchange  
 440 scenario, certain entities must have specific attributes and values and can also be  
 441 used in the validation of IFC files. The IfcDoc tool also allows the definition of  
 442 new concept templates such as the schedule concept. This feature helps users to  
 443 define multiple concepts and properties that support a specific exchange scenario  
 444 and can surpass the reusable templates provided by buildingSMART. Another  
 445 feature of the IfcDoc tool is the exchange requirements table (Figure 14), which  
 446 summarises the entities and concepts for export once the MVD is implemented  
 447 in a BIM application. Each concept defines a graph of entities and attributes,  
 448 with constraints and parameters set for attributes and instance types. Various  
 449 entities within this schema reference such concept templates and adapt them for  
 450 a given exchange scenario. It is important to note that several sets of exchange

451 requirements can be defined within a unique MVD, thus, providing a range of  
452 possibilities for different scenarios.

453     The left side of the matrix shown on Figure 14 contains the objects used in  
454 the MVD definition for BEPS, while the relevant concepts are at the top of the  
455 matrix . The chosen approach cross references the object and concepts in order  
456 to identify relationships between them. These relationships vary from case to  
457 case where a concept: is incompatible with the entity (dark grey), is not rele-  
458 vant for the MVD definition (light grey), is compatible but not in the scope of  
459 the exchange (white) and is mandatory (green) or optional (blue) for the export  
460 function. Once the MVD is complete, IfcDoc generates the HTML documen-  
461 tation containing the subset of IFC entities, properties and concepts that were  
462 specified for the exchange between BIM and BEPS tools. This documentation  
463 serves as basis for vendors to implement import/export functions on their BIM  
464 applications. For instance, if a BIM software has already implemented the MVD  
465 for BEPS, the output IFC file will contain only the exchange requirements de-  
466 fined for energy analysis, reducing the amount of irrelevant information. This  
467 approach, can reduce the time necessary to collect the information from different  
468 sources.



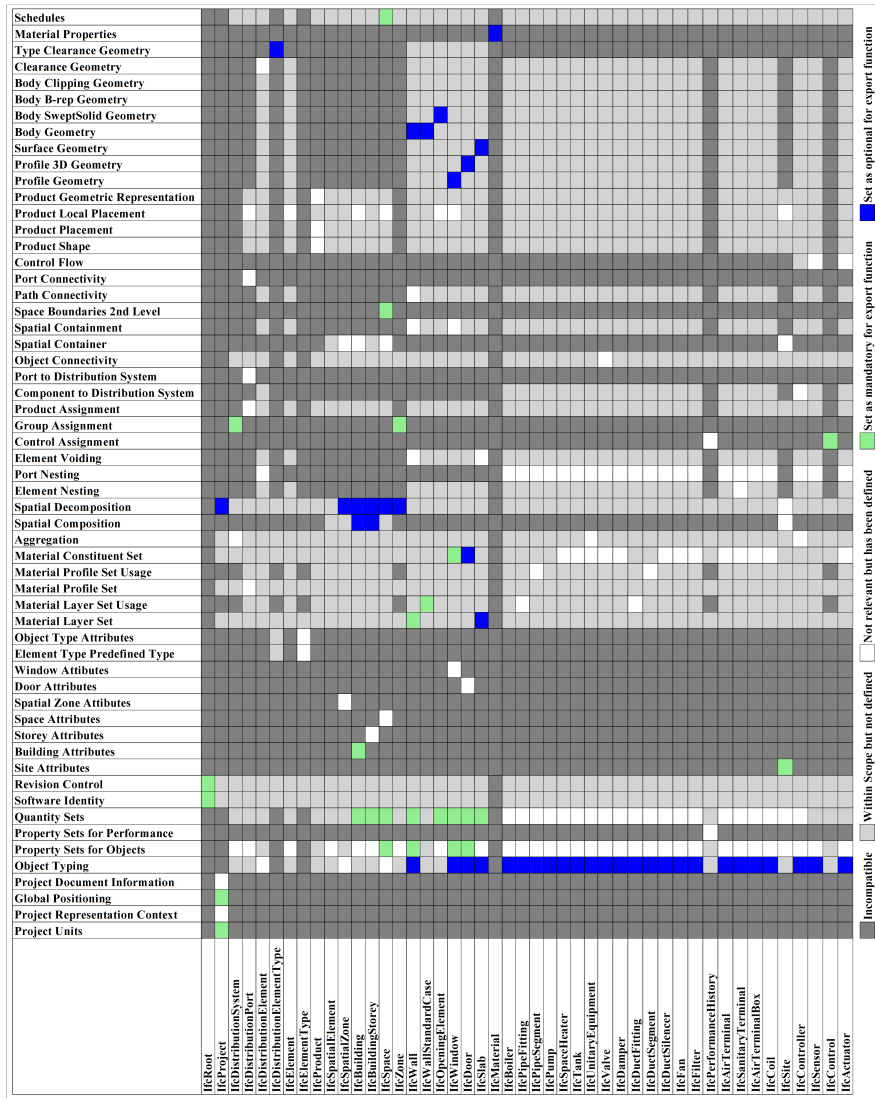


Figure 14: Summary of the exchange requirements (entities and concepts) defined in the MVD for building energy performance simulation.

## 469 5. Discussion and Limitations

470 IFC is a rich model that addresses the need for different applications and  
471 provides a variety of ways to define the same part of a building. For this reason,  
472 implementer agreements are used to limit the different ways to define the same  
473 concept inside an MVD. Even though IFC is a vast data model, BEPS tools will  
474 typically require additional data to properly execute, data that are not included  
475 in nor are subject to an MVD. While such data are not exchangeable as part  
476 of an MVD-based/defined data exchange, they are commonly provided to the  
477 simulation directly by the end user without using IFC.

478 The results from this study showed that IFC4 brought major improvements  
479 in the HVAC extension with more complex and complete definitions of com-  
480 ponents and systems. However, the latest release of the schema is still lacking  
481 important component definitions such as Heat Pumps and CHPs. The addi-  
482 tion of such complex definitions to the IFC schema is time consuming due to  
483 the standardised certification process, which must account for complex building  
484 designs and relatively simple cases. For this reason, the IFC schema provides  
485 general entities for use in such cases (e.g. IfcUnitaryEquipment, IfcBuildingEle-  
486 mentProxy, etc). These types of entities, together with user-defined property  
487 sets and the concept of predefined type, accommodate different cases that are  
488 not specified in the current IFC schema and provide a work-flow to cover such  
489 cases. If an international consensus is reached the IFC schema can be extended  
490 to cover these specific scenarios. Data models of this type are reactive by their  
491 nature to industry advances, especially in cases including new technology, reg-  
492 ulations and work processes that had not been considered previously.

493 The MVD has been designed to be a general purpose view of BEPS. The  
494 development of the MVD is based on the defined use cases and is limited to  
495 the HVAC objects contained within these use cases and the latest version of the  
496 IFC schema. Changes to the MVD will be required when new data types are  
497 introduced to the IFC schema or when data requirements of BEPS tools are  
498 re-defined. The MVD contains all key concepts related to building performance

simulation but further specifications of the MVD should include the HVAC components that were not contained in the use cases. Most of the effort is required when initially designing the MVD, updates are typically an order of magnitude less onerous. It is also important to point out that export and import of IFC is the responsibility of software vendors i.e. new software versions do not require new MVDs.

The introduction of MVD concepts is a positive development in terms of intended re-usability, as each concept is standalone and complete, allowing the concept to be assigned to various building elements. In the MVD definition, available concept templates were re-used as far as possible, but a number of inconsistencies or missing concepts were identified during the project:

- Missing pattern definition for schedules,
- Missing explicit entities for heat pumps and CHP units,
- Missing agreement on system hierarchy and
- Missing possibility to define nested properties for complex properties with the IfcDoc tool.

When defining new MVD concepts, it is important to follow strict and formal procedures so the final definition can be testable. By making the MVD concept a strongly typed system, it can contribute to a better understanding of model views by providing a concise view of the exchange scenario. Furthermore, it can help achieve a uniform mapping of IFC entities and relationships.

One of the limitations encountered during the development of the MVD is that most BIM applications do not provide in house IFC4 export capabilities. For instance, Revit provides an add-on to overcome this issue but still lacks a flawless IFC4 file generation according to the ISO 16739. Additionally, we have found that for Revit System Families (such as pipe segment, pipe fitting, duct segment, etc.) we could not assign property sets to IFC types. The only way to export properties for system families was to set the required shared parameters

527 as either instance or type parameters in Revit and then export them to the  
528 corresponding instance entity in IFC. For example, property sets for pipes could  
529 only be exported to IfcPipeSegment and not to IfcPipeSegmentType.

530 The certification process provided by buildingSMART is still under devel-  
531 opment for IFC4. Once official certification of IFC4 begins, the quality of IFC  
532 files should drastically improve and better results could be achieved. Yet an-  
533 other limitation is the quality of BIMs due to the fact that most applications do  
534 not instantiate the IFC file properly, in particular to HVAC controls where the  
535 object and property definitions required by BEPS are not rigorously specified.  
536 While model checking tools exist and are further developed, the understanding  
537 of providing data models of high quality is not yet present in practice. In order  
538 to overcome this issue, the rule-based method developed in the paper builds  
539 a base to represent the simulation-related data quality and checks whether a  
540 designated model is compliant with the requirements.

## 541 **6. Conclusion**

542 This work successfully demonstrated that IFC MVD can be used as a stan-  
543 dardised method for information exchange within the building sector. IFC-based  
544 information exchange has the potential to provide significant inputs for BEPS  
545 (and other tools), thus reducing the time, effort and expense associated with  
546 model creation. Furthermore, the formally defined view for energy analysis can  
547 address the issue of efficient information exchange with minimal downstream  
548 cleaning of the model.

549 The MVD developed in this paper applies the methodology from buildingS-  
550 MART and uses the recommended IfcDoc tool for its formal and descriptive  
551 definition. IfcDoc enables the export of HTML documentation and mvdXML  
552 format (official buildingSMART format) for software certification and genera-  
553 tion of a subset schema containing all relevant entities and properties. This pro-  
554 cess aims to reduce the issues encountered in the process of manually re-entering  
555 data into energy simulation models by enabling a semi-automatic generation of

556 IFC files that capture the exchange requirements needed by energy simulation  
557 from BIM.

558 As mentioned, previous efforts on MVD development focused on geometry  
559 data with little specification of HVAC components and properties. In addition to  
560 geometry information, a proper MVD for energy analysis should contain HVAC  
561 objects, controls, operating schedules and simulation parameters in the data  
562 exchange. The successful articulation of the model view serves as an open plat-  
563 form for a more robust way of certifying applications that support the process  
564 of energy analysis. It is important to notice that the process of certification is  
565 done based on MVDs and not the general IFC schema. The certification process  
566 requires time and depends on buildingSMART as well as software developers.

567 The final step in the development is the submission of an MVD proposal  
568 to buildingSMART for further review by the community as well as to extend  
569 its scope to cover all relevant HVAC objects. In parallel to the review period,  
570 the software certification process can be prepared, which means to specify test  
571 cases and expected quality criteria. Thus, the developed use cases and prepared  
572 example data can be used as a starting point, as they already cover the main  
573 aspects of the presented use cases, but may need to be extended to check further  
574 aspects of the MVD.

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